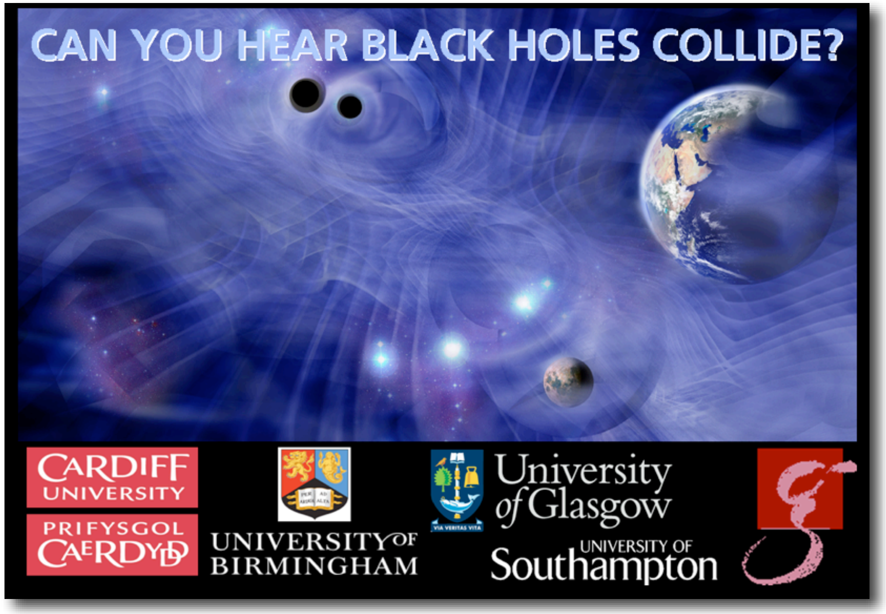
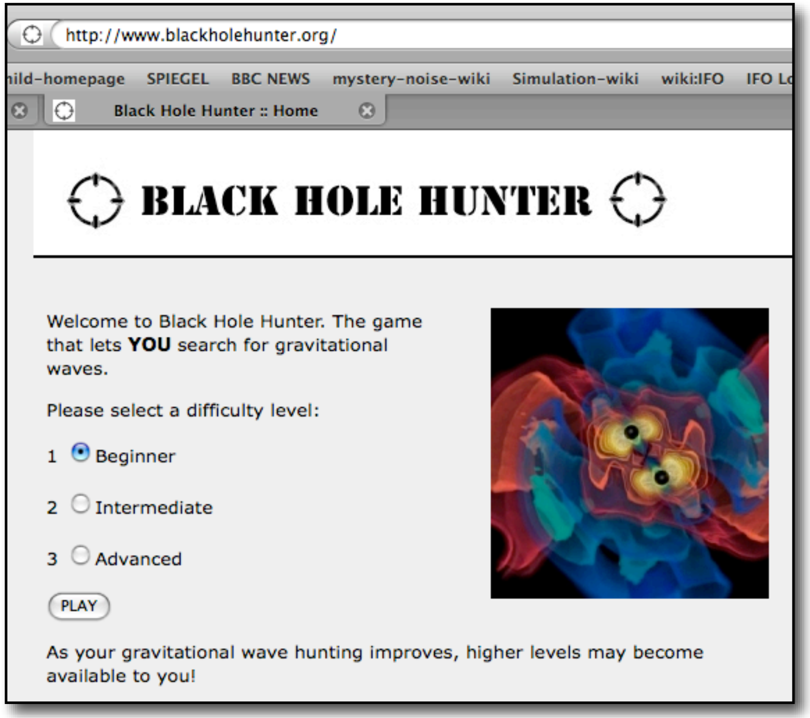
Hunting Gravitational Waves: Present and Future

Stefan Hild, **University of Birmingham, UK**

Astro physics seminar,
Fermilab, December 2008

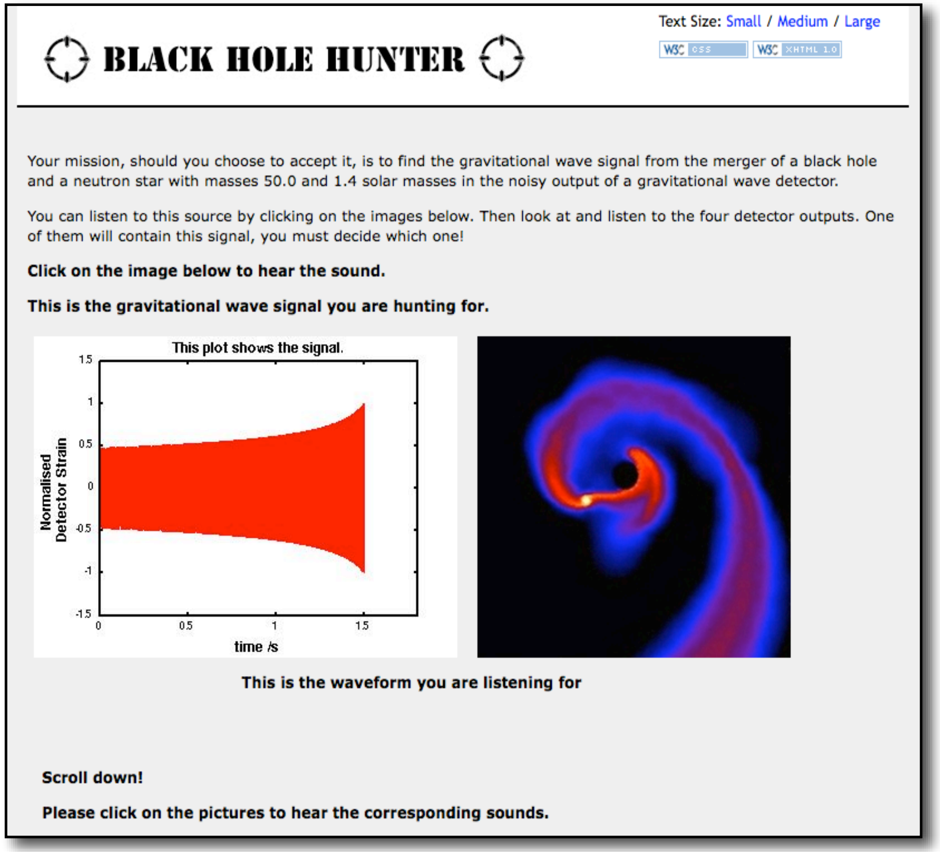
Let's start with some fun

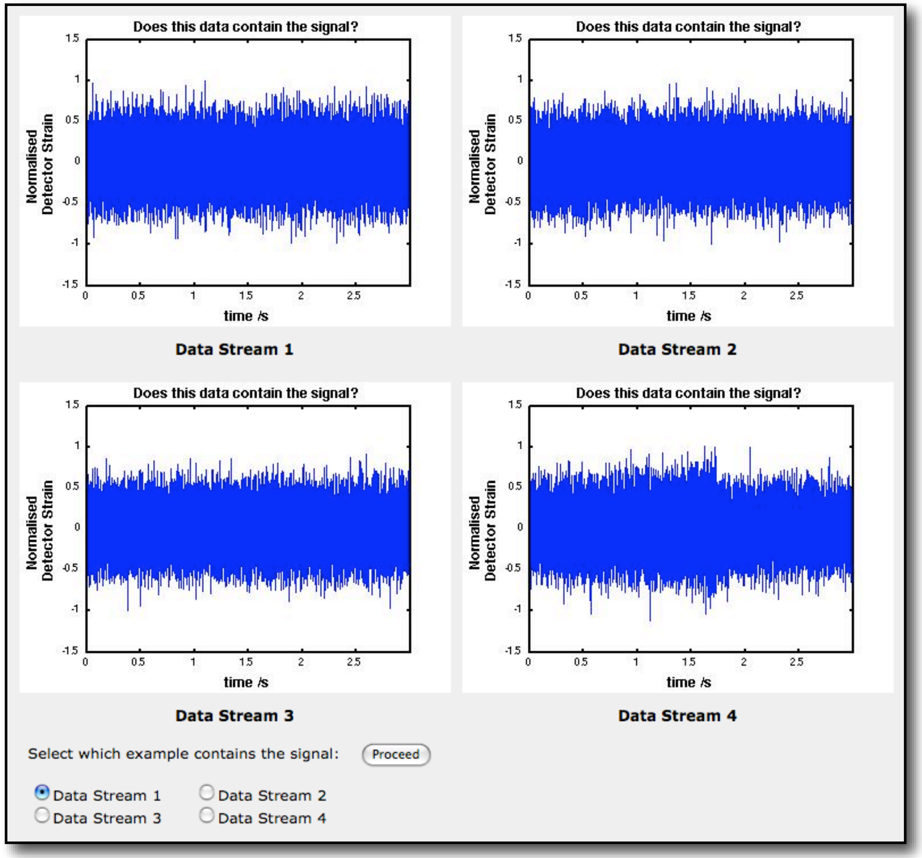




- British Royal Socienty summer exhibition: http://www.summerscience.org.uk/

Black Hole Hunter





- Give it a try at your next lunch break… :)

Overview

- What are gravitational waves?
- How can we convert gravitational waves into a digital data stream?
  - How does a GW interact with laser light?
  - How far can we boost up the signal by clever interferometry?
  - How to calibrate a gravitational wave detector?
  - What type of noise spoil our efforts?
- When will we detect the first gravitational wave?
- What will future gravitational wave detectors look like?

Looking at a dark spot in the sky

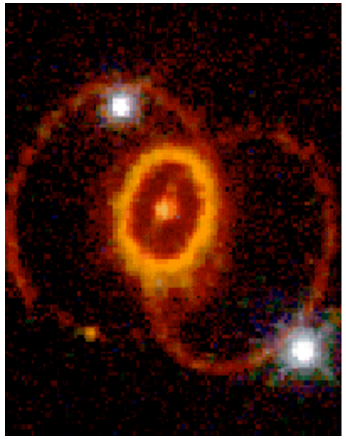
- For ages mankind has been looking towards the stars wondering about the origin of the Earth and the whole Universe.

http://hubblesite.org/newscenter/archive/releases/2004/07/video/b

- Today we know the Universe is a zoo of exciting phenomena.

Gravitational waves: A new window to the Universe

- Nearly all of our current knowledge of the cosmos is based on observation of electromagnetic radiation (visible light, radio astronomy, infrared, ...).
- Gravitational astronomy can open a completely new window to the universe:
  - *<u>Multimessenger observations:</u>* We can learn more about things we already see in the electromagnetic spectrum by also seeing their GW emission (for instance supernovae).
  - *<u>Exclusive GW observations:</u>* There are objects that can only be seen by their GW emission



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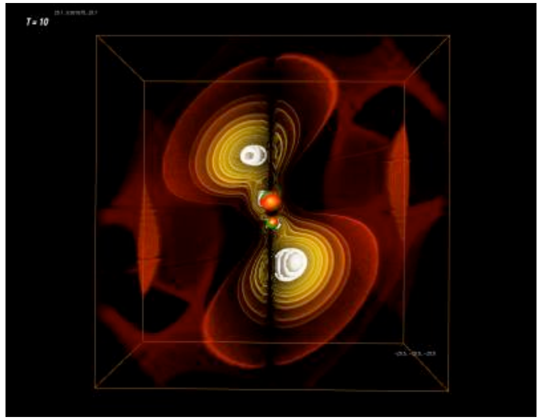
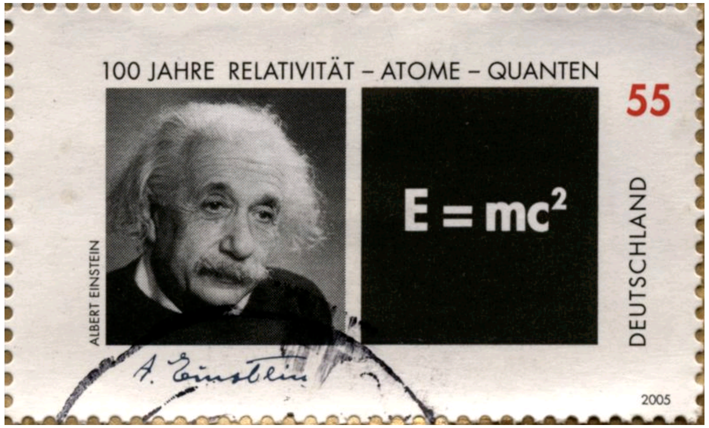


http://numrel.aei.mpg.de/Visualisations/

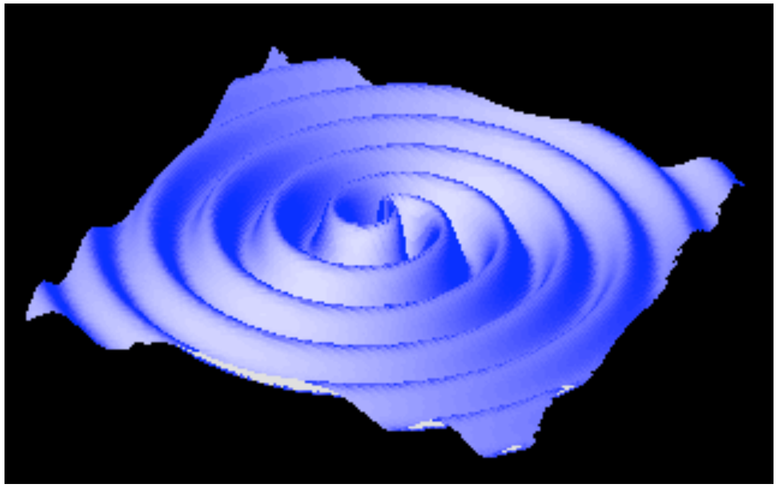
What are gravitational waves ?

- GW are a prediction of General Relativity: Changes of gravitational fields are not instantaneous (Newton), but travel with the speed of light (Einstein).



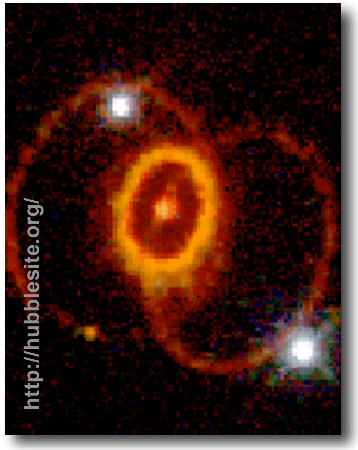
- GW are ripples in spacetime.

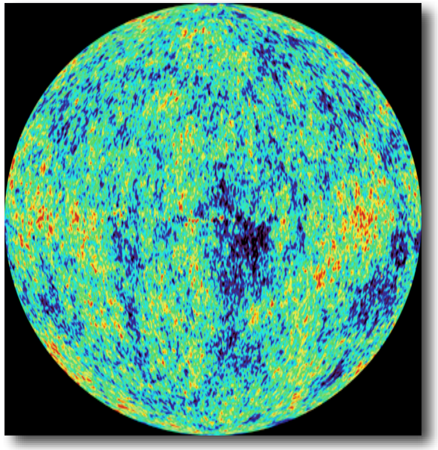
- GW originate from (asymmetric) accelerated masses

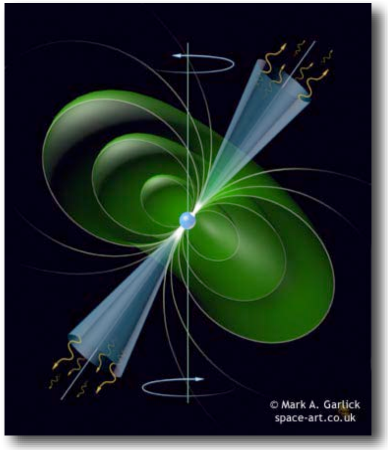


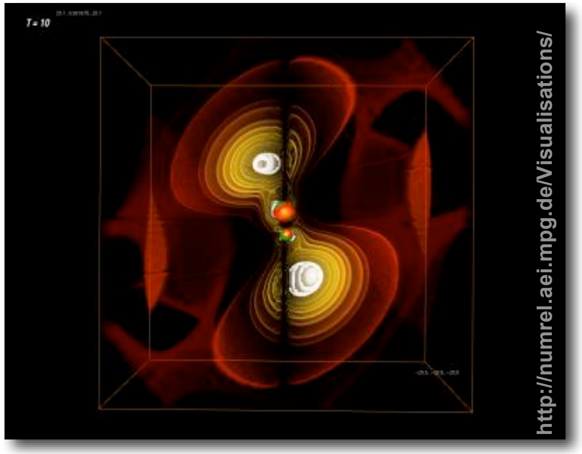
Sources of Gravitational Waves we may see with Advanced Virgo

Colliding black holes, inspiraling neutron stars, pulsars, supernovae, aftermath of the Big Bang …









Why haven't we seen GW so far?

Stress Energy Tensor

Metric Tensor

$$\boxed{\overline{\overline{T}} = \frac{c^4}{8\pi G}\overline{\overline{G}}}$$

Stiffness of space time

$$\boxed{\frac{c^4}{8\pi G} \approx 5 \cdot 10^{42}}$$

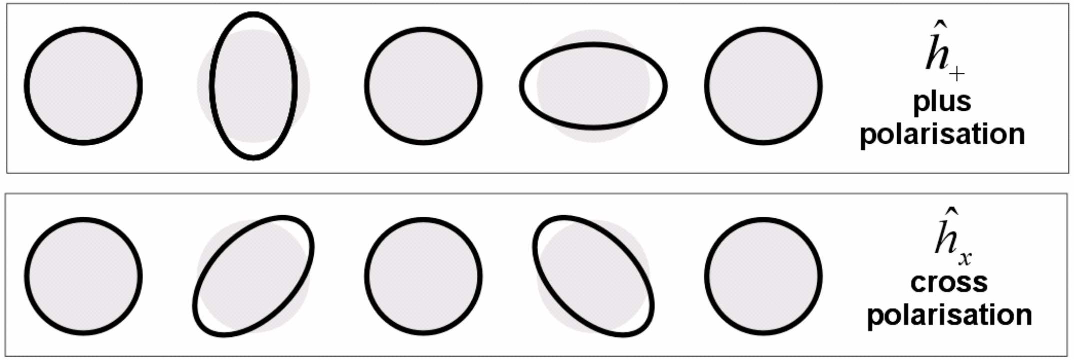
Analogon: Hooke's law

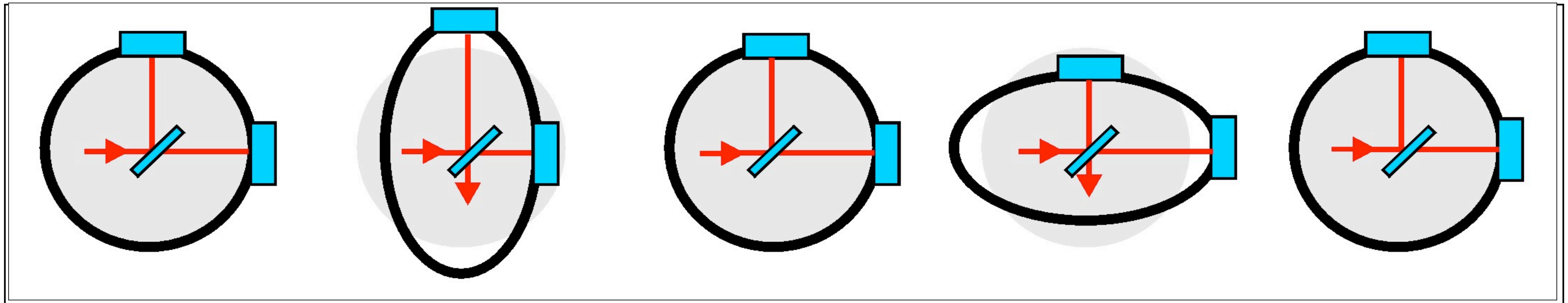
$$(\vec{F} = k\vec{x})$$

- Space time is extremely stiff !
- Length changes are really tiny ($<10^{-21}$) !

How can we detect gravitational waves?

A Michelson interferometer is the ideal instrument to measure relative length changes.



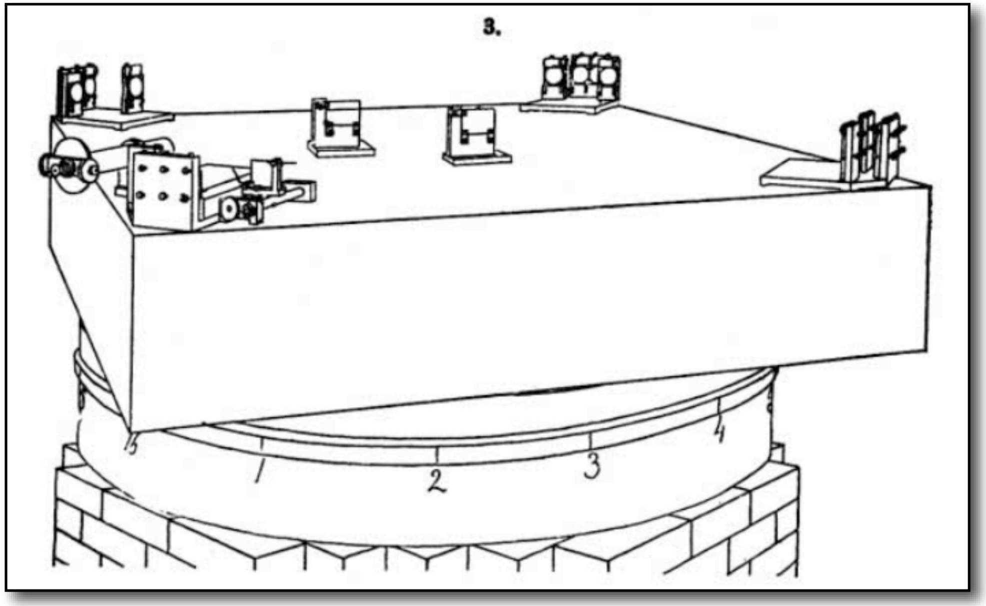


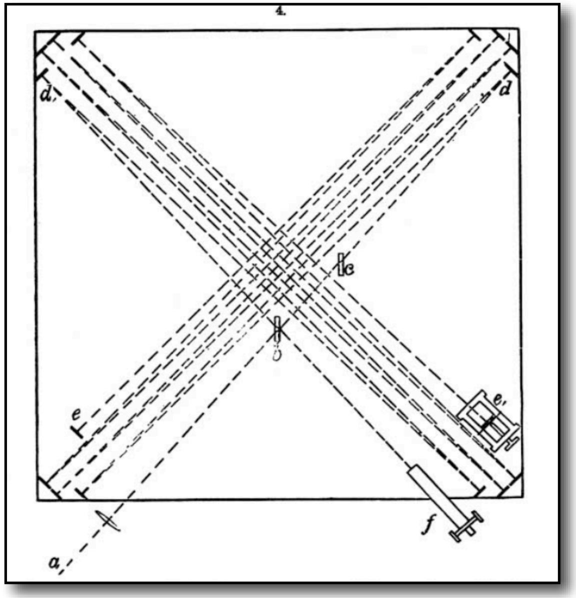
$L_1 = L_2$	$L_1 > L_2$	$L_1 = L_2$	$L_1 < L_2$	$L_1 = L_2$
destructive	**Light @ output**	**destructive**	**Light @ output**	**destructive**

Going back to the starting point

- The first Michelson interferometer: Experiment performed by Albert Michelson in Potsdam 1881.
- Measurement accuracy 0.02 fringe (expected Ether effect ~0.04 fringes)
- Outcome: Not conclusive

Michelson in Cleveland, Ohio





- 2nd attempt in 1887, together with Morley.
- Increased optical pathlength (multiply-folded arms)
- Improved seismic isolation: Mercury bath (also stopping traffic around the laboratory building).

The first science derived from an Michelson interferometer

No. 203. Vol. XXXIV. NOVEMBER, 1887.

Established by BENJAMIN SILLIMAN in 1818.

THE

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THIRD SERIES.

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ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

* This research was carried out with the aid of the Bache Fund.

† It may be noticed that most writers admit the sufficiency of the explanation according to the emissiou theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

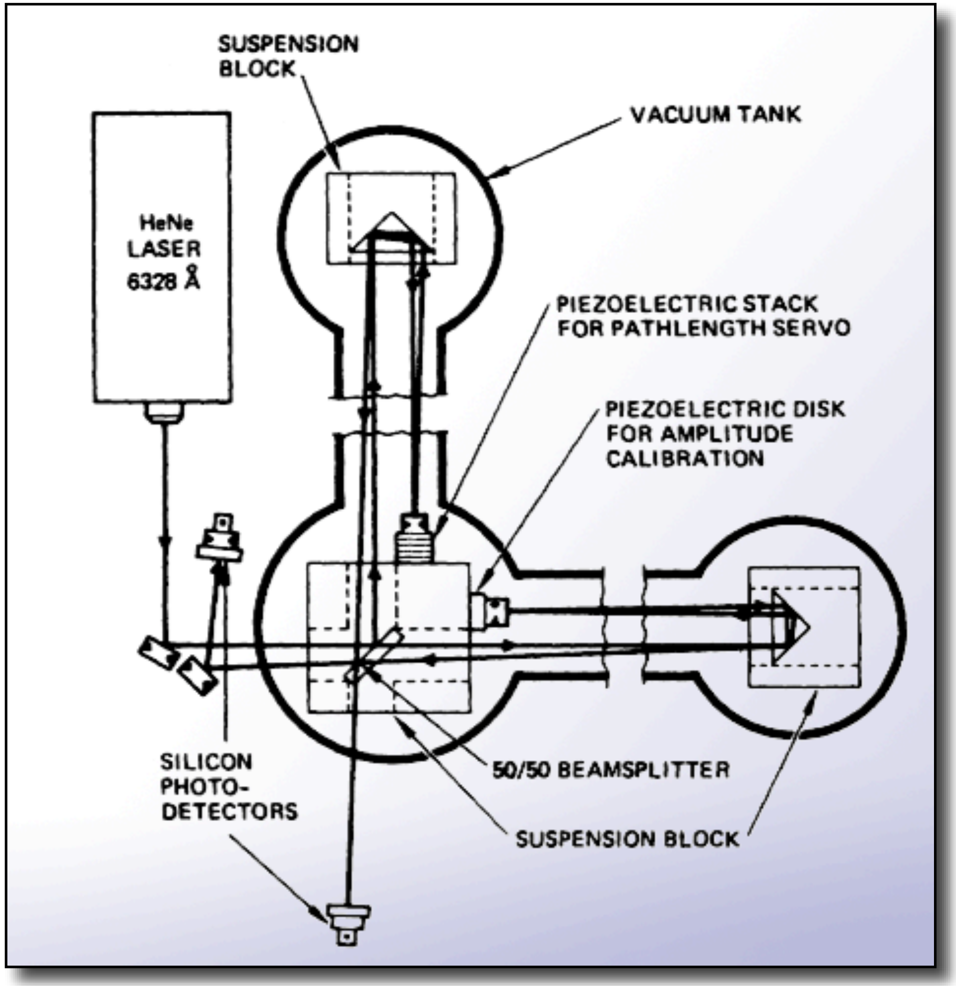
AM. JOUR. SCI.—THIRD SERIES, VOL. XXXIV, No. 203.—NOV., 1887.
22

- Measurement accuracy 0.01 fringes, expected Ether effect ~0.4 fringes

Michelson Interferometer

1970s:

- Weiss/Forward: first idea and realisation of a Michelson-based gravitational-wave detector
- Sensitivity: 10^{-8} of a fringe



Today's network of GW detectors

Today:

- LIGO, GEO600 and Virgo
- Sensitivity: 10^{-13} of a fringe

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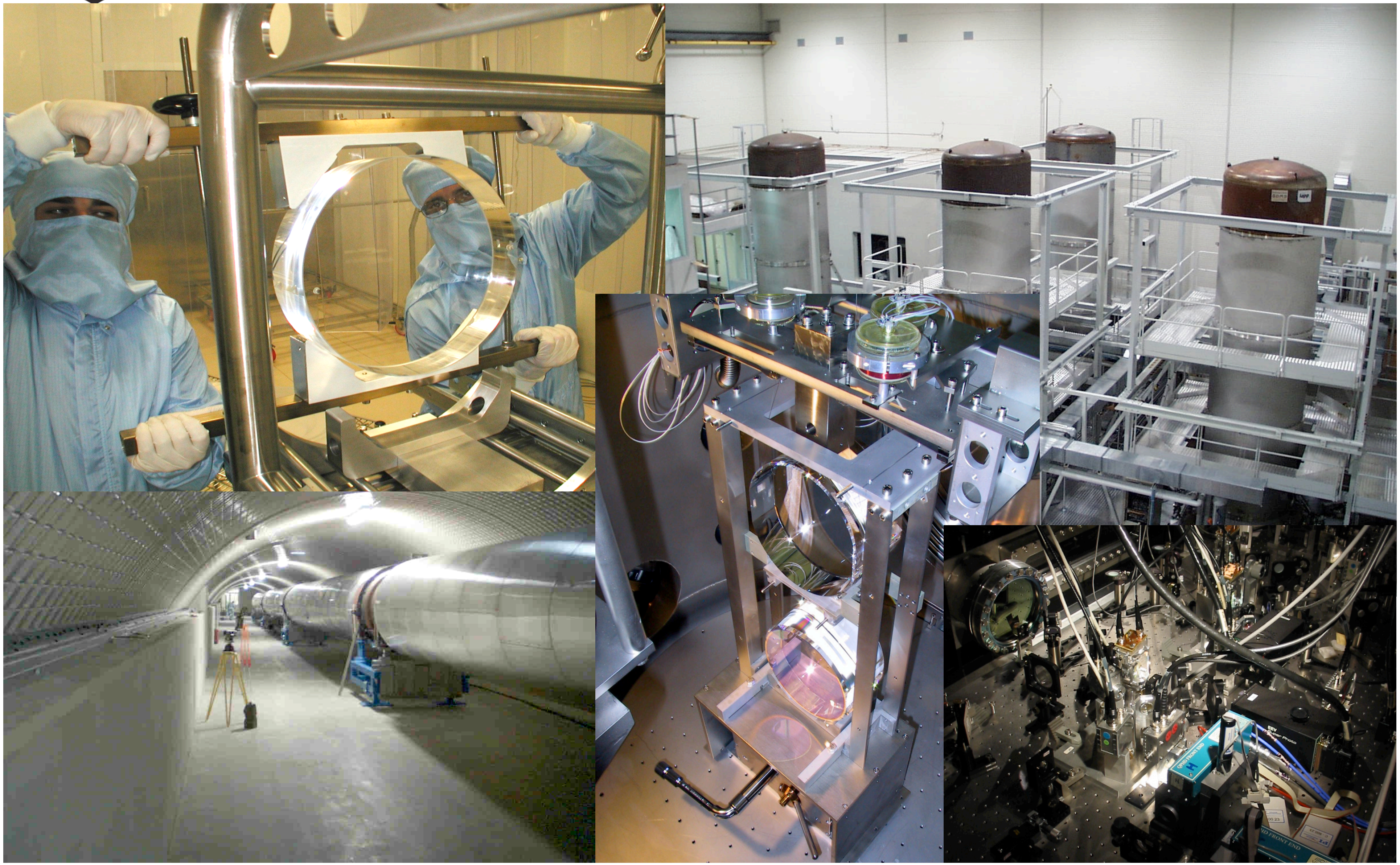
State-of-the-art Michelson



What lengths changes can be resolved?

Example: GEO600 can measure the its arm length of

600 meter

with a resolution of:

$2x10^{-19}$ meter

0.0000000000000000002 meter (!!!)

1/10000 of a proton diameter

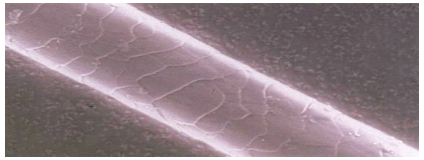
at a frequency of 500 Hz.

This is equivalent to measuring a length of

1 billion times the circumference of the earth

with a resolution of the

diameter of a human hair.



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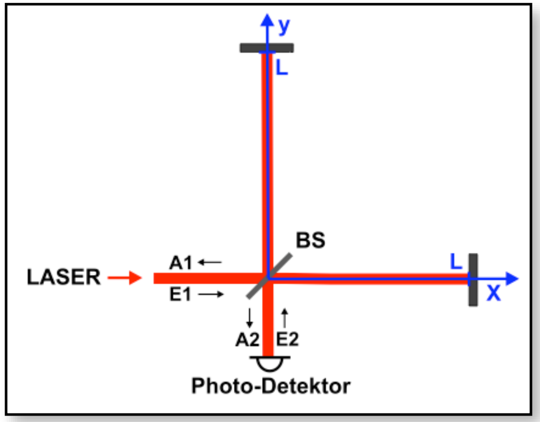
Interaction of GW and laser light

TT-gauge: Test masses don't move => but GW changes the distance between test masses:

$$ds^2 = -cdt^2 + (1+h_+)dx^2 + (1-h_+)dy^2 + dz^2 = 0.$$



Only considering x-arm:

$$\frac{dx}{dt} = \frac{c}{\sqrt{1+h_+}}.$$

$$2L = \int_0^L dx - \int_L^0 dx = \int_{t-\tau}^{t} \frac{dx}{dt'}dt' = \int_{t-\tau}^{t} \frac{c}{\sqrt{1-h_+(t')}}dt' = c\tau - \frac{1}{2}c\int_{t-\tau}^{t} h_+(t')dt'.$$

Travel time in x-arm

$$\tau_x = \frac{2L}{c} + \frac{1}{2}\int_{t-2\frac{L}{c}}^{t} h_+(t')dt',$$

Interaction of GW and laser light (2)

Phase

Laser freq

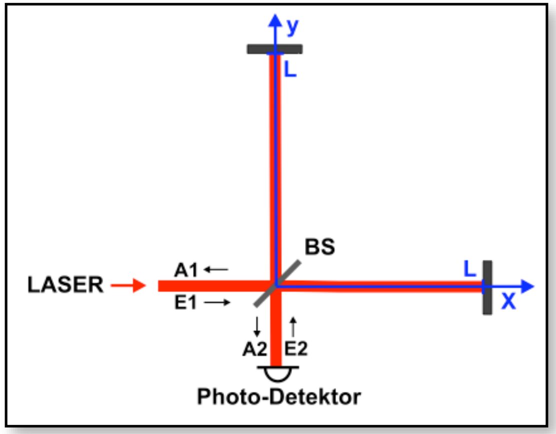
$$-\varphi = \omega_0 \tau_x$$

$$h_+(t) = h_0 cos\omega_g t$$

Assumption of GW signal

GW amplitude

GW freq



$$\tau_x = \frac{2L}{c} + \frac{1}{2}\int_{t-2\frac{L}{c}}^{t} h_+(t')dt',$$

$$-\varphi(t) = 2\frac{L}{c}\omega_0 + \frac{\omega_0}{2}\int_{t-2\frac{L}{c}}^{t} h_+(t')dt' = 2\frac{L}{c}\omega_0 + h_0\frac{\omega_0}{\omega_g}\sin(\omega_g\frac{L}{c})\cos(\omega_g(t-\frac{L}{c})).$$

Phase shift Produced by GW

$$\boxed{\Delta\varphi(t) = h_0\frac{\omega_0}{\omega_g}\sin(\omega_g\frac{\tau}{2})\cos(\omega_g(t-\frac{\tau}{2})).}$$

Geometry term

Optimal arm length

Maximum Signal:

$$\Delta\varphi(t) = h_0 \frac{\omega_0}{\omega_g} \underbrace{\sin(\omega_g \frac{\tau}{2})}_{=1} \cos(\omega_g (t - \frac{\tau}{2})).$$

Optimal Arm length:

$$L = \frac{\lambda_g}{4}$$

GW wavelength

Example: GW signal at 100 Hz
=> optimal arm length of 750 km (!!)

For short arms: develop sine term

- Signal proportional to h_0, w_0, L
- Signal independent from GW frequency

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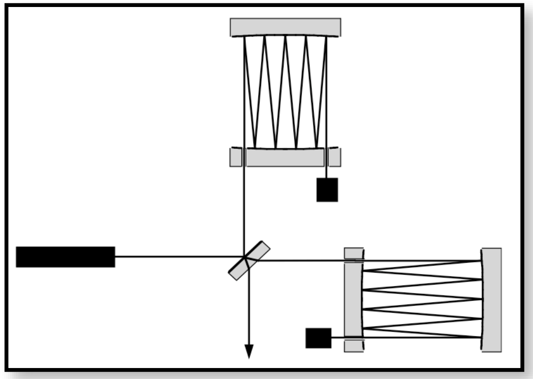
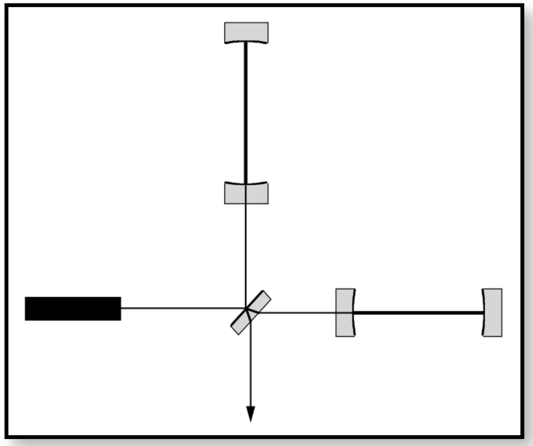
Increasing the optical arm length

- Several techniques available to increase the optical arm length for constant physical arm length:

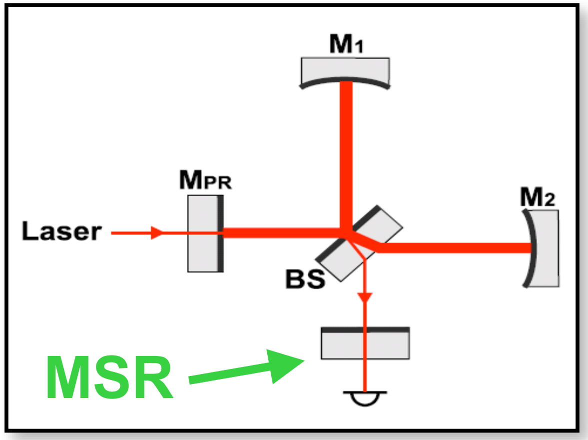




  - **Delay lines**
    - Not in use any more.
  - **Fabry-Perot resonatoren**
    - Used by LIGO and Virgo
  - **Signal Recycling**
    - At the moment only GEO
    - Advanced LIGO and Advanced Virgo will use it

Signal-Recycling in short

- An additional recycling mirror **(MSR)** at the output port allows:
  - Enhancing the GW signal in a certain freuency range
  - Decrease of GW signal at other frequencies
  - Allows shaping of detector response
- So far only used by GEO600, but will be used by all future detectors.

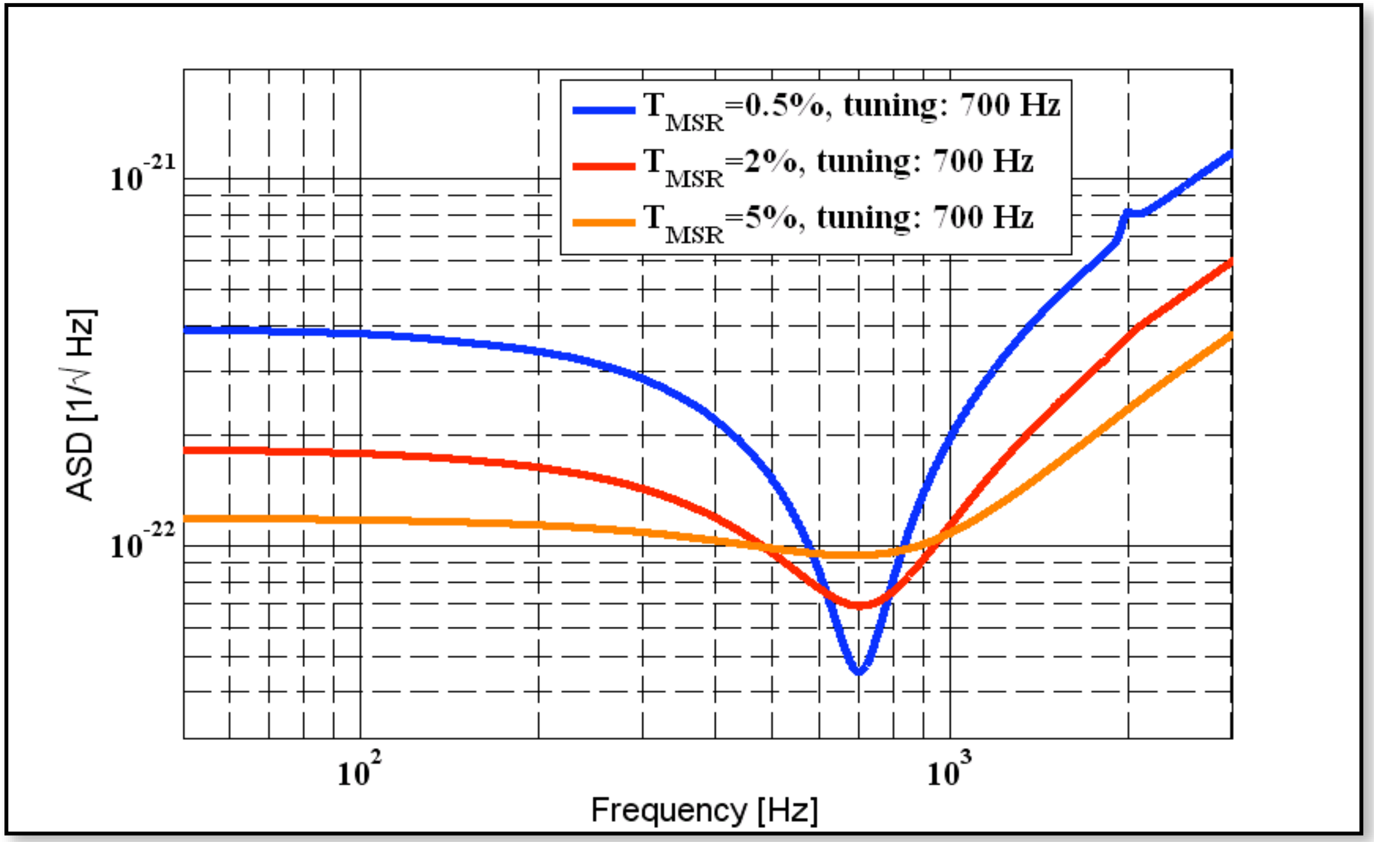


Two main parameters:

- **Bandwidth** (of the SR resonance) → broadband / narrowband
- **Tuning** (Fourier frequency of the SR resonance) → tuned / detuned

Bandwidth of Signal-Recycling

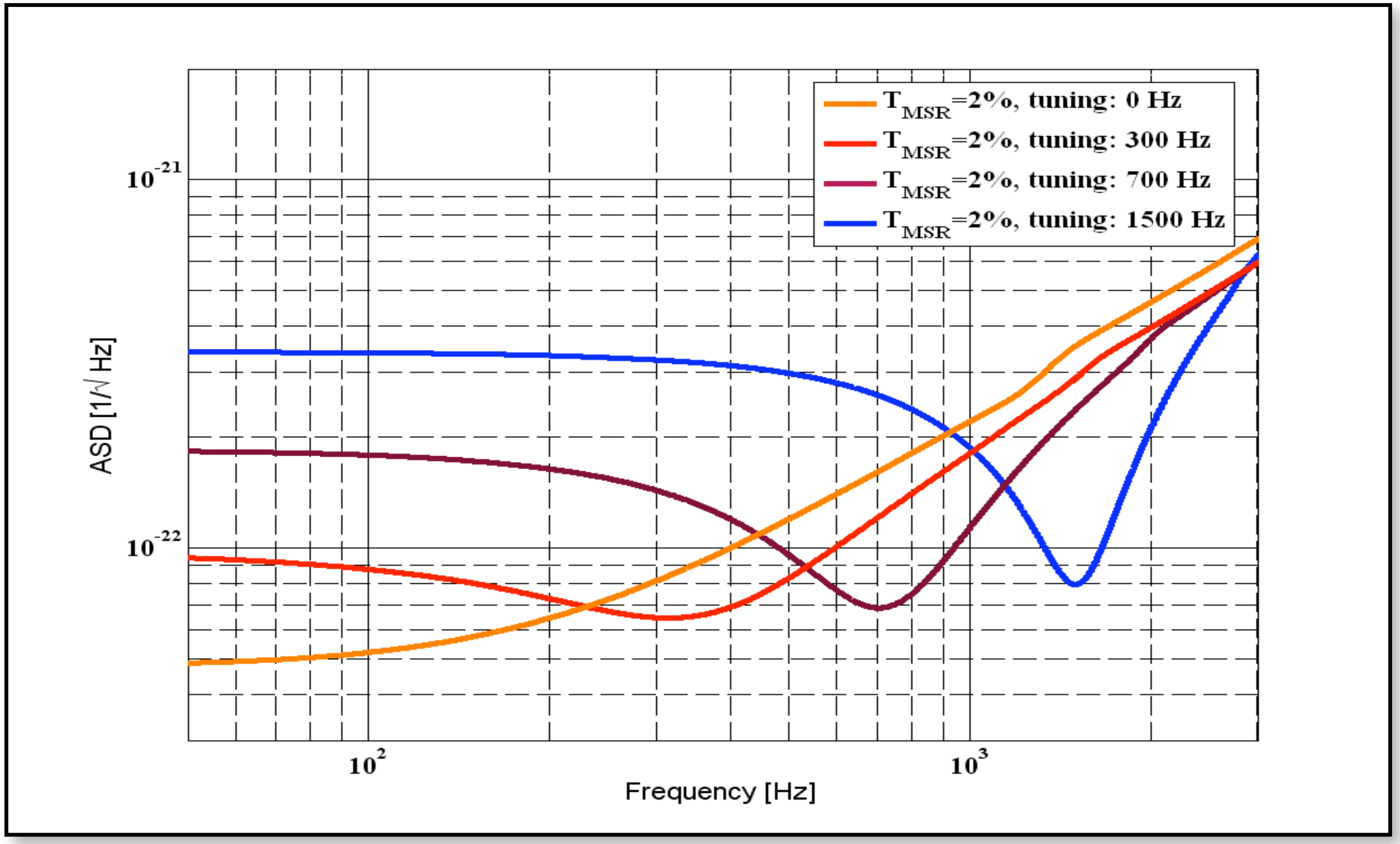
Shot noise for GEO600 with a light power of 10 kW @ beam splitter



The bandwidth of the Signal-Recycling resonance is determined by the reflectivity of MSR.

Tuning of Signal-Recycling

Shot noise for GEO600 with a light power of 10 kW @ beam splitter



The tuning of the Signal-Recycling resonance is determined by the microscopic position of MSR.

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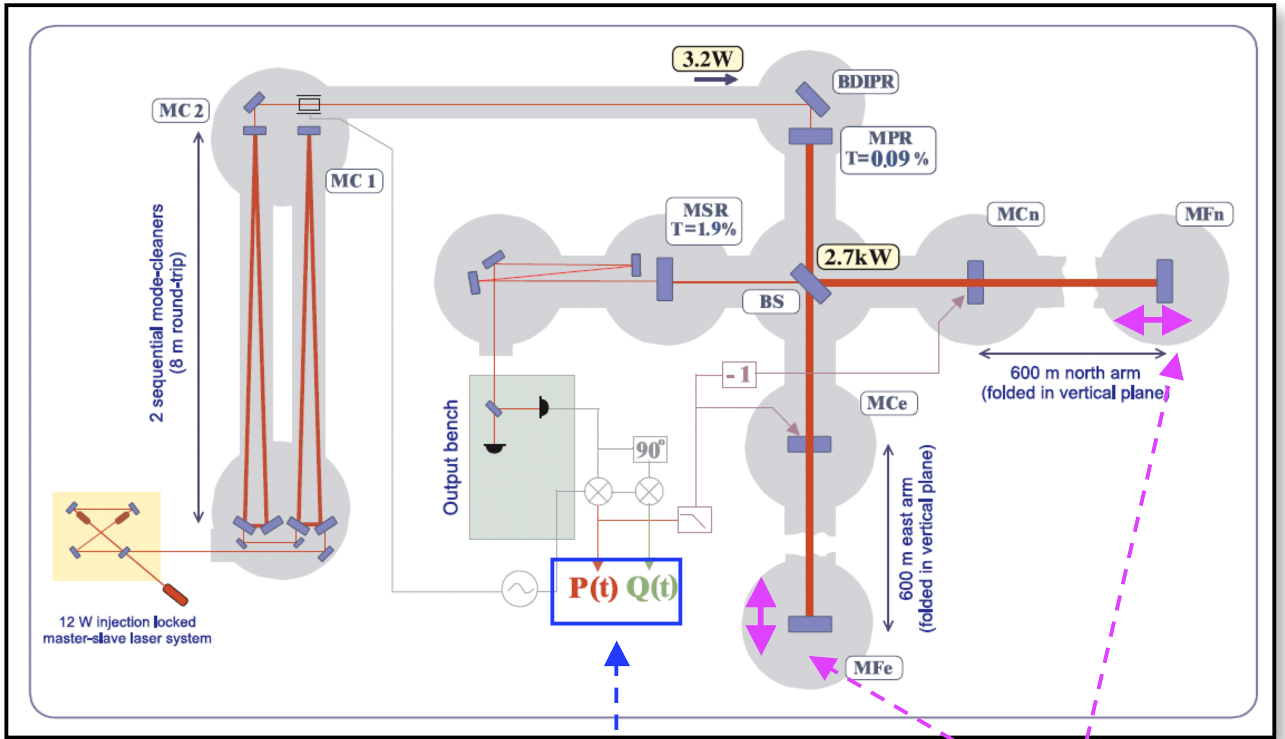
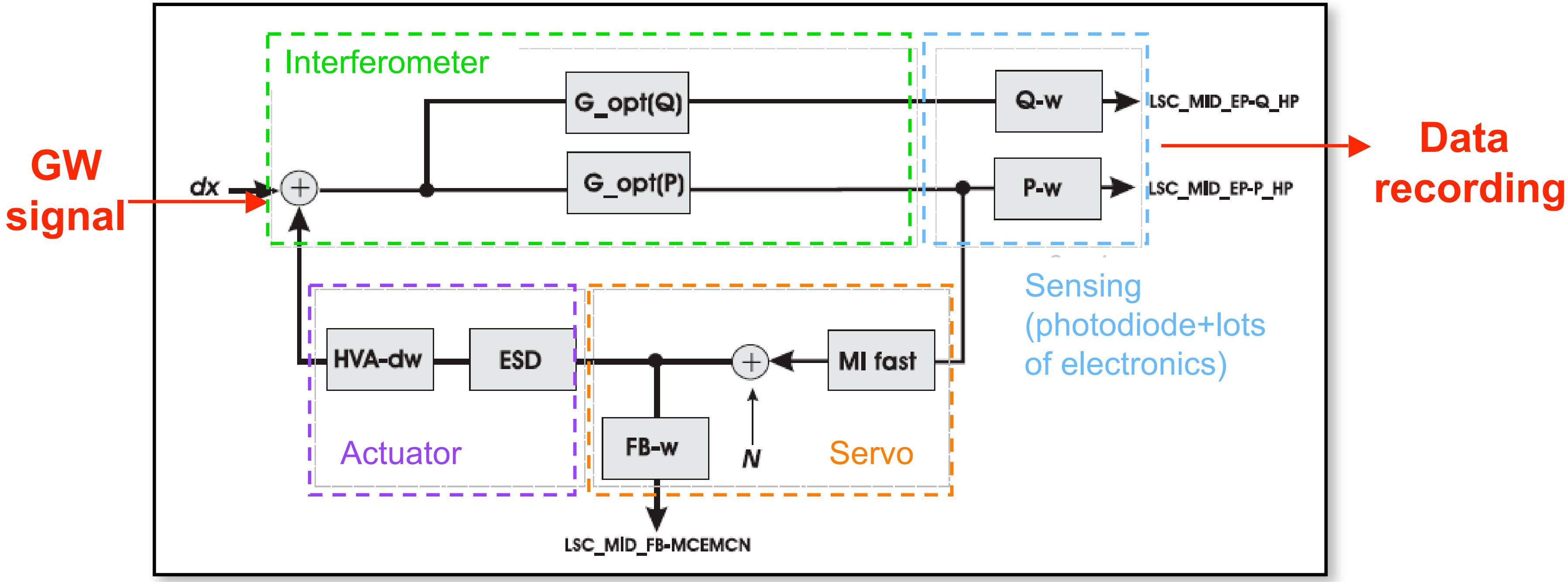
How to calibrate a GW detector ??



- Task: Calibrate photo diode signal (Voltage) to differential arm length change, i.e. GW signal:
  - Including feedback loops
  - Absolute calibration + relative calibration (frequency dependent)

Calibration model



- Need to know all transfer functions of involved electronics (sensing, recording, servo etc) and actuators.
- Main problem: Interferometer transfer function changes with time => have to measure optical TF continuously.

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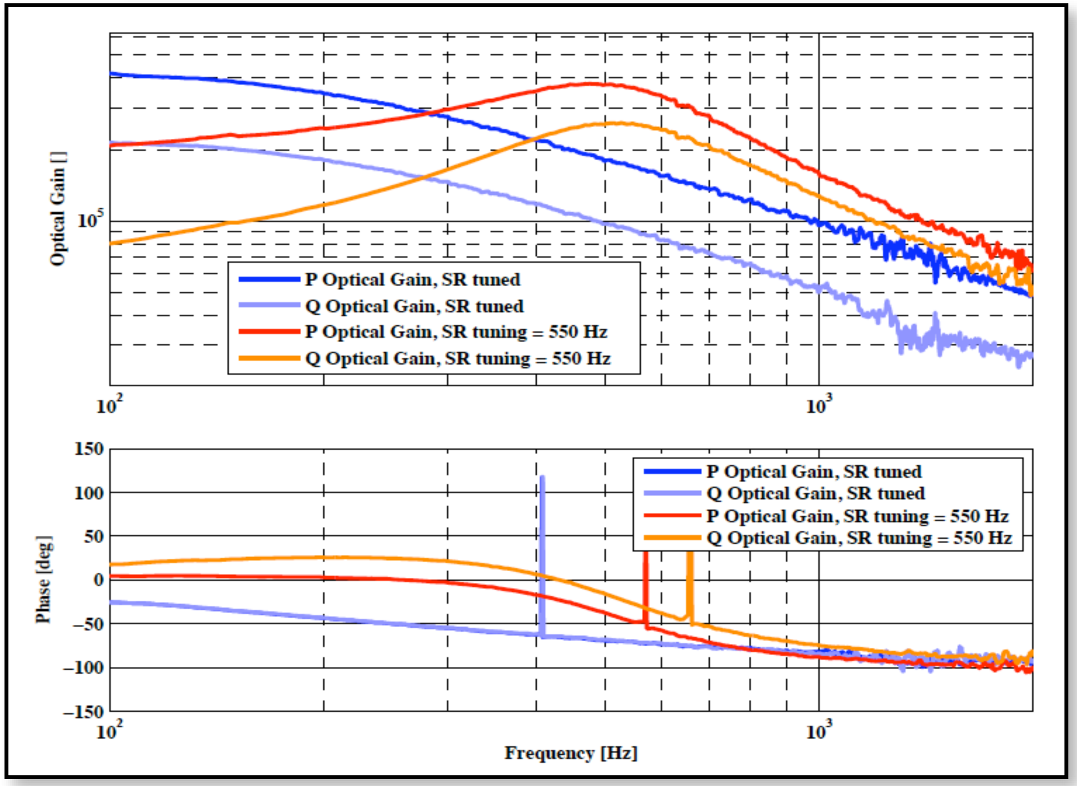
How to determine the optical gain?

- Method1: offline-broad-band noise injection
  - Gives a good calibration at all frequencies
  - Cannot be used during measuring operation
  - Only gives the calibration for one point in time

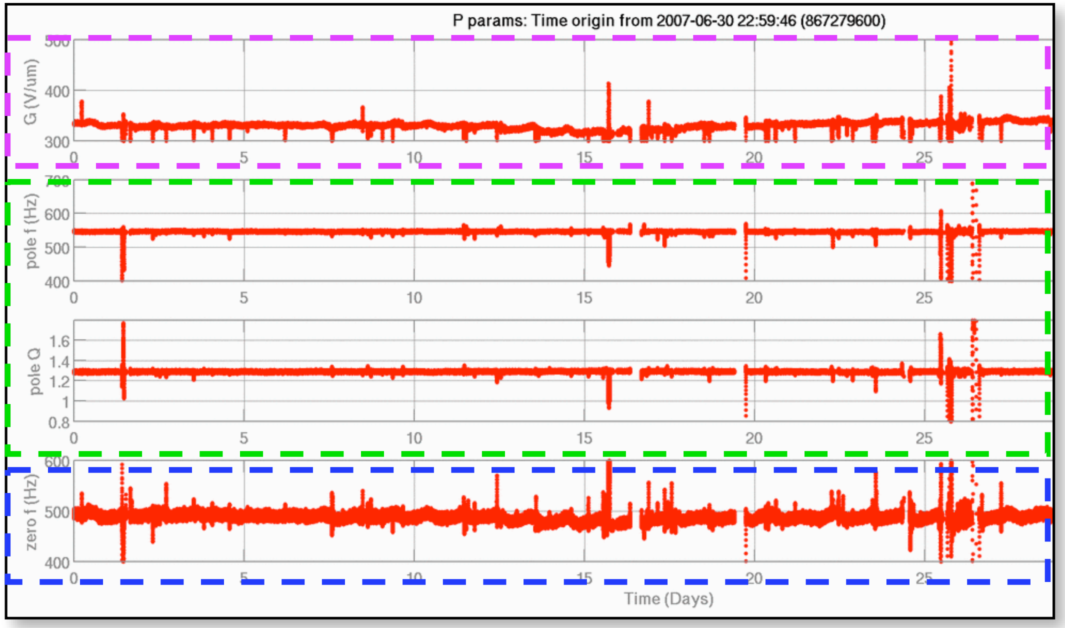
$$G\_opt(P) = \frac{\text{EP-P} \cdot \text{P-dw}}{\text{FB} \cdot \text{FB-dw}} \cdot \frac{1}{\text{ESD}} \cdot \frac{1}{\text{HVA-dw}}$$



How to determine the optical gain?

- Method2: calibration using injected calibration lines
  - Estimates the calibration parameter at only a few frequencies
  - Allows continuous online calibration
  - Chi² used to check the calibration accuracy.

Optical response of the detector can be modeled by four parameters:
Complex pole (2), zero, overall gain



2 Calibration examples

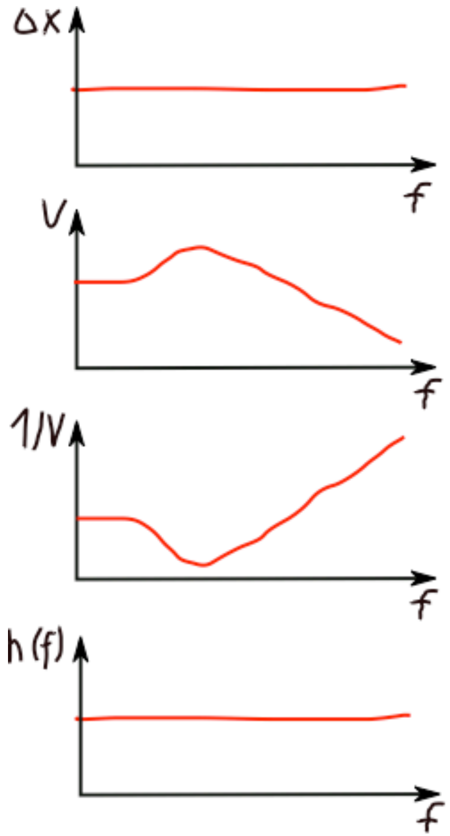
Displacement noise of a testmass

Spectrum of displacement

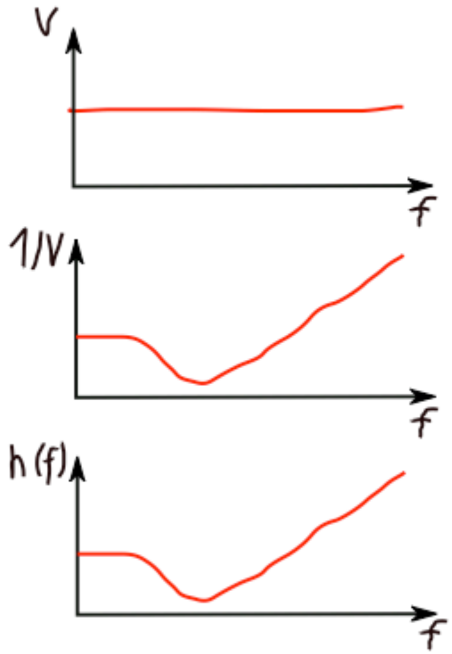
Voltage at photodiode

Calibration process: Multiply by inverse optical gain

Calibrated Strain



Photon shot noise



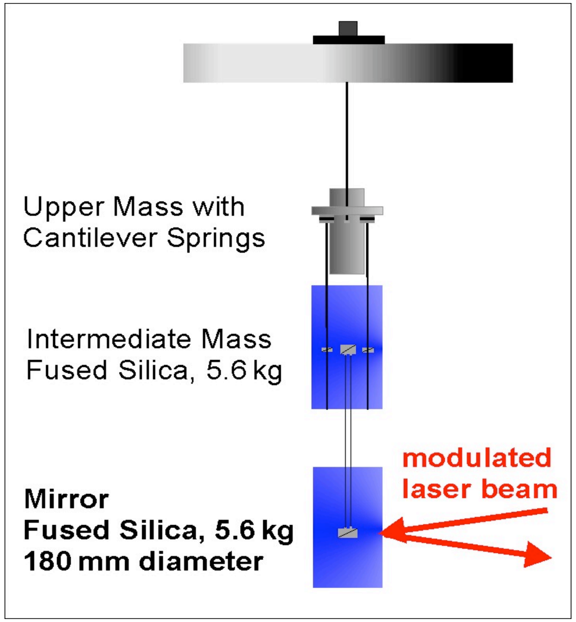
Voltage at photodiode

Calibration process: Multiply by inverse optical gain

Calibrated Strain

Independent verification of the calibration: Photon pressure

- Accurate calibration is required for any kind of astrophysical parameter extraction.
- A high calibration accuracy is essential for multi-detector analysis (null-stream, coherent).
- Official calibration is a very complex procedure involving several steps (accumulating errors).
- Photon pressure calibration can give an independent check of the calibration, employing a very simple physical relation:



$$x(\omega) = \frac{2 \cdot P}{M \cdot c \cdot \omega^2}$$

Even less than 1mW modulated power can move the mirror (5.6 kg) !!

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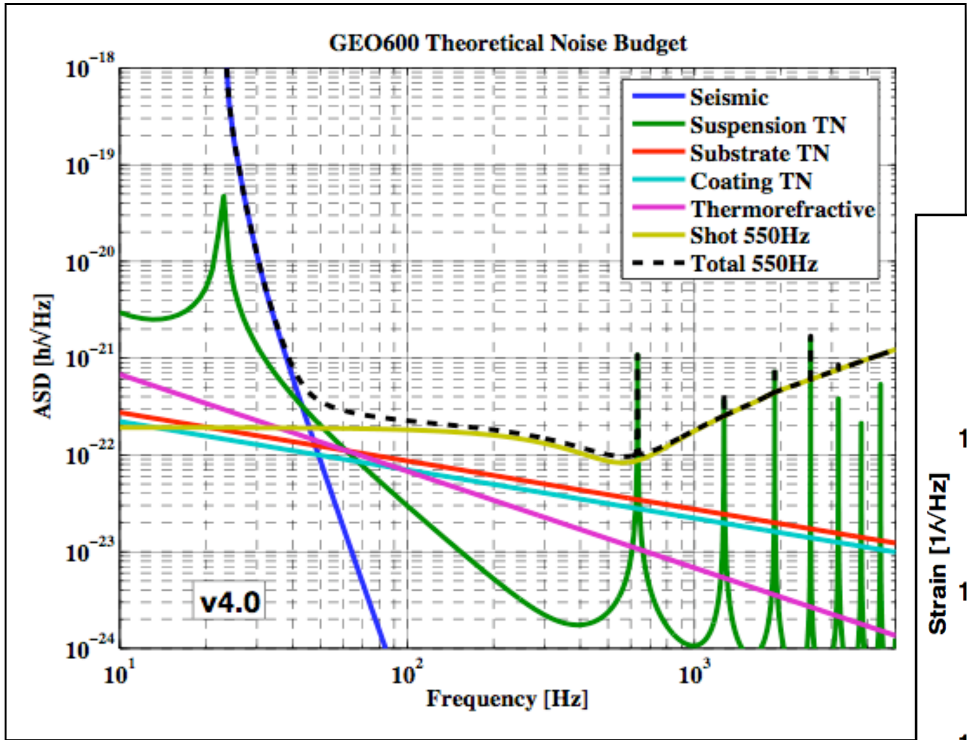
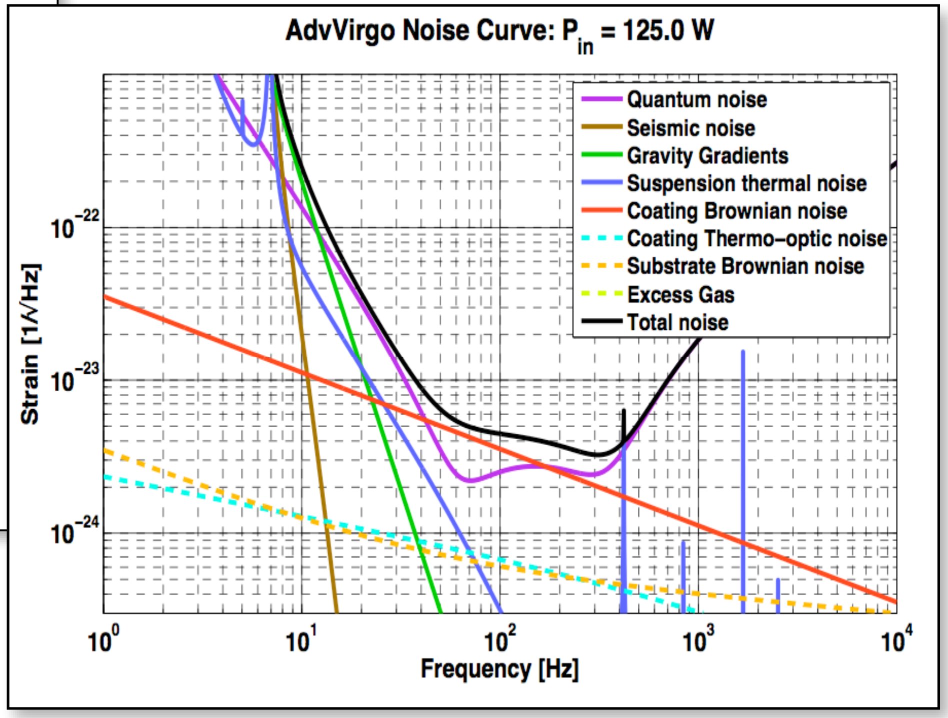
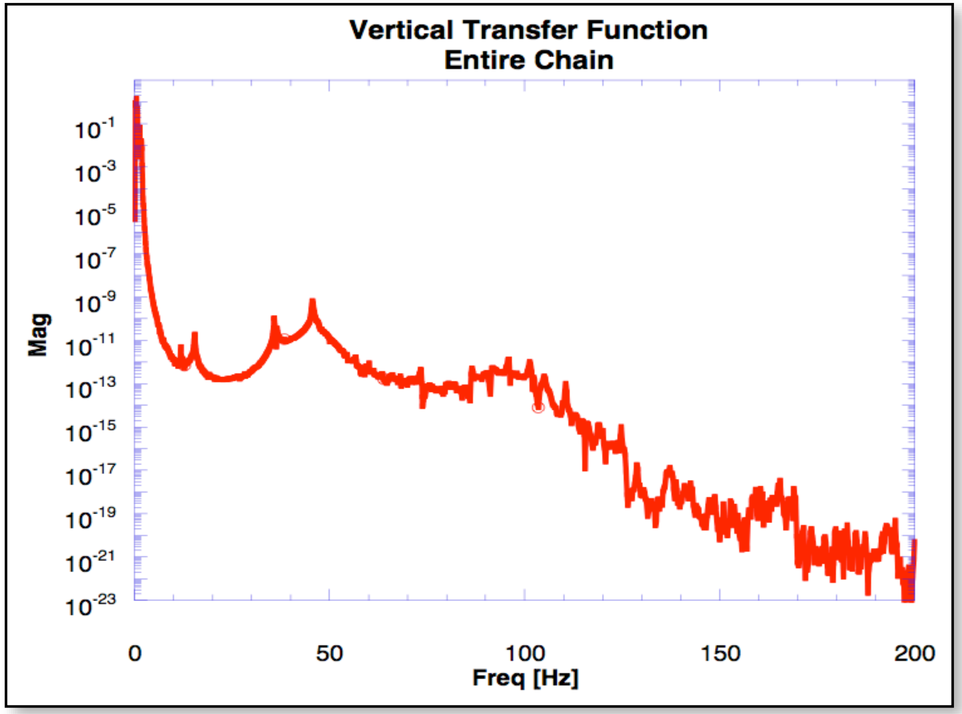
Fundamental noises: 2 Examples

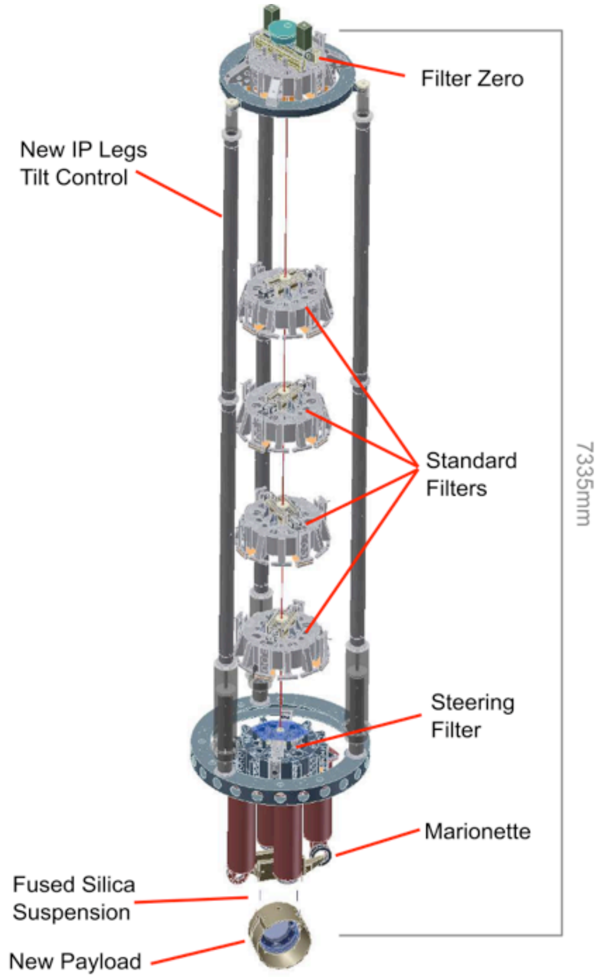




Example of seismic Isolation

- The Virgo 'Super attenuator' is the most sophisticated seismic isolation currently in operation.





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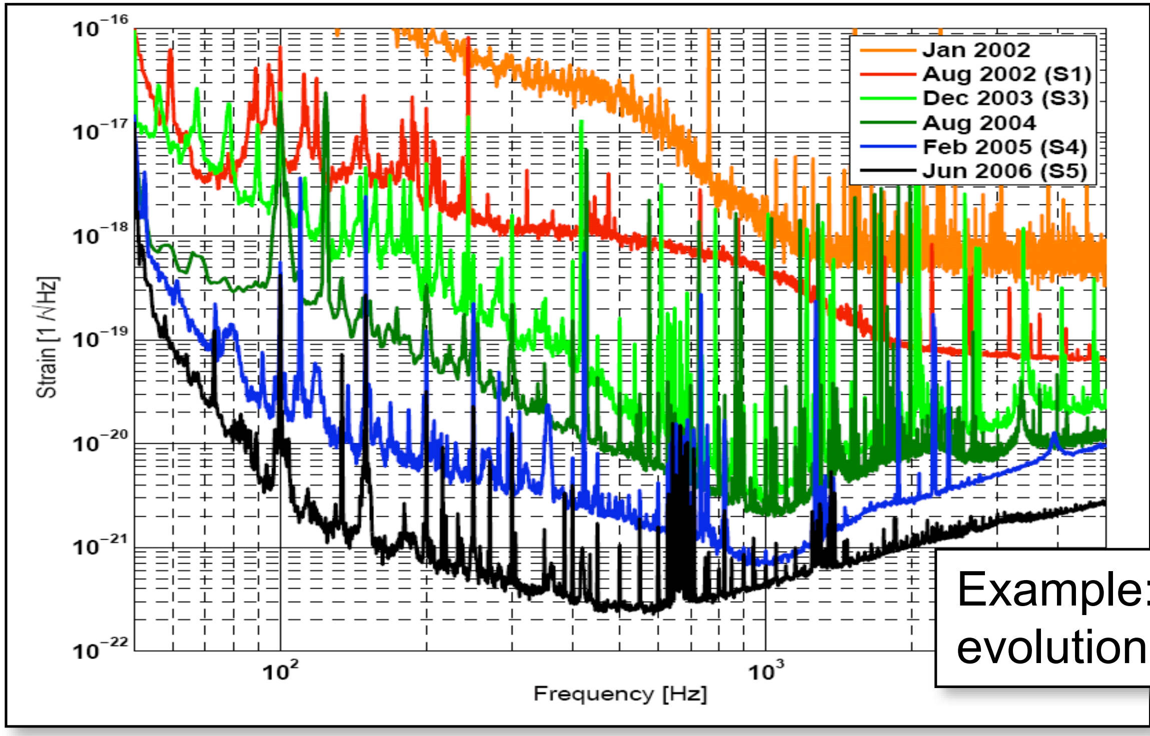
Technical noises

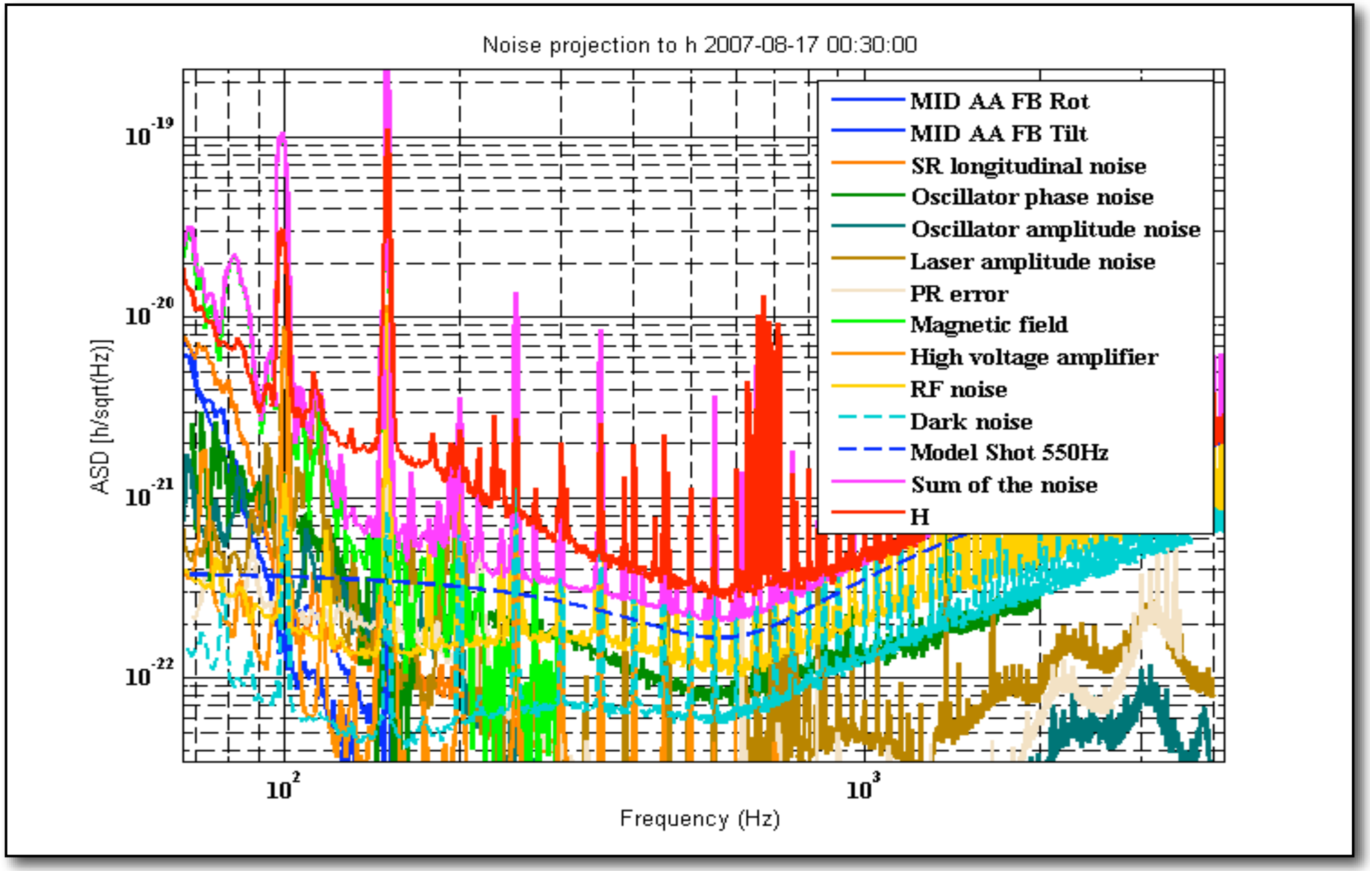
- The main challenges of today's GW detectors are technical noise sources, such as laser frequency noise or alignment noise.



Example: Sensitivity evolution of GEO600

- It took years to bring LIGO, GEO and VIRGO (close) to their design sensitivities

Technical noises



- In GEO600 there is a gap between the sum of all explained noises and the measured sensitivity.

Holographic noise in GEO ???

Can the unexplained noise in GEO600 be explained by holographic noise?

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Measurement of quantum fluctuations in geometry

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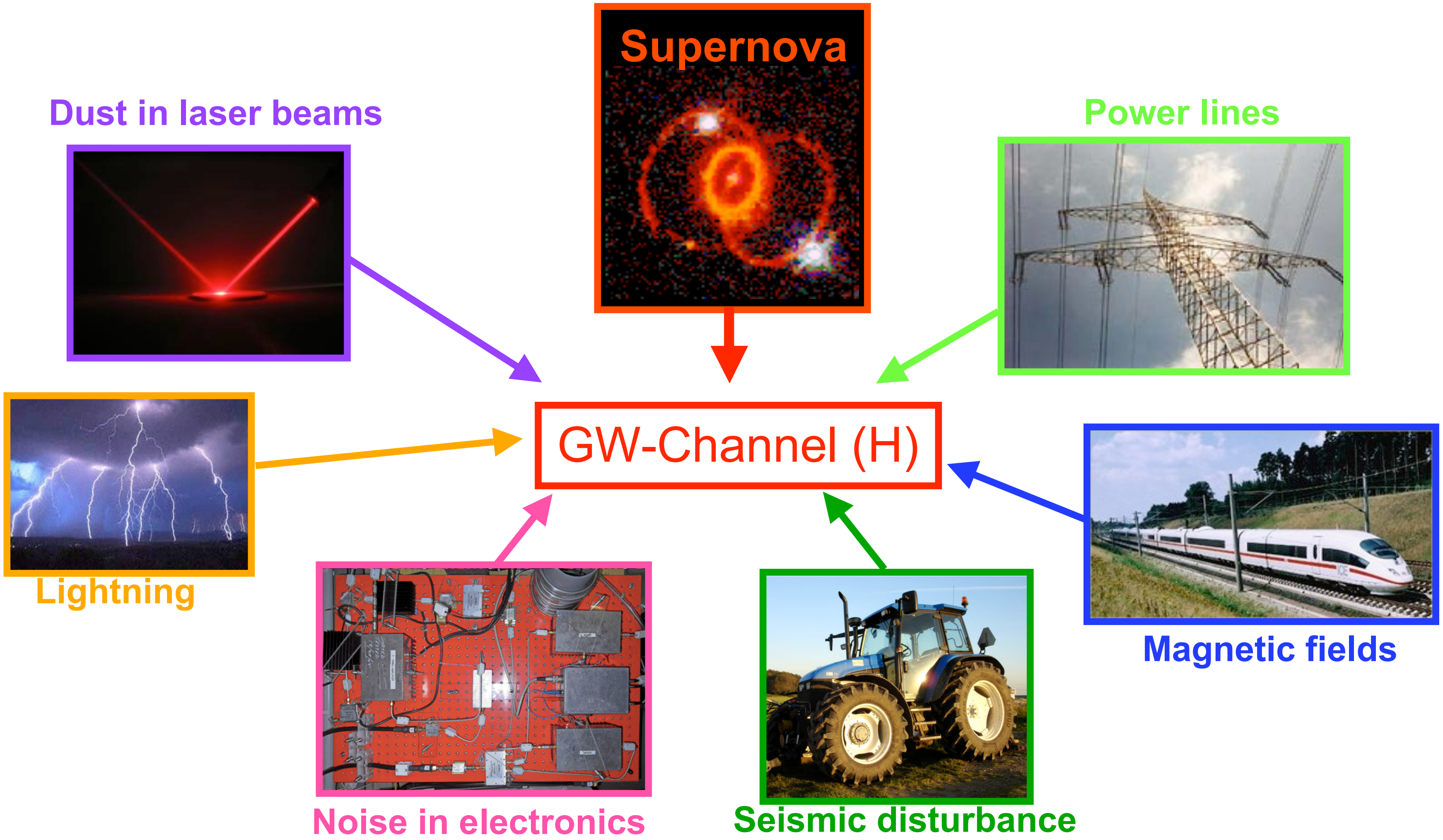
University of Washington, Seattle, Washington 98195-1580, USA
(Received 21 December 2007; published 28 May 2008)

A particular form for the quantum indeterminacy of relative spacetime position of events is derived from the context of a holographic geometry with a minimum length at the Planck scale. The indeterminacy predicts fluctuations from a classically defined geometry in the form of "holographic noise" whose spatial character, absolute normalization, and spectrum are predicted with no parameters. The noise has a distinctive transverse spatial shear signature and a flat power spectral density given by the Planck time. An interferometer signal displays noise due to the uncertainty of relative positions of reflection events. The noise corresponds to an accumulation of phase offset with time that mimics a random walk of those optical elements that change the orientation of a wavefront. It only appears in measurements that compare transverse positions and does not appear at all in purely radial position measurements. A lower bound on holographic noise follows from a covariant upper bound on gravitational entropy. The predicted holographic noise spectrum is estimated to be comparable to measured noise in the currently operating interferometric gravitational-wave detector GEO600. Because of its transverse character, holographic noise is reduced relative to gravitational wave effects in other interferometer designs, such as the LIGO observatories, where beam power is much less in the beam splitter than in the arms.

DOI: 10.1103/PhysRevD.77.104031 PACS numbers: 04.60.Bc

Plenty of varying noise sources

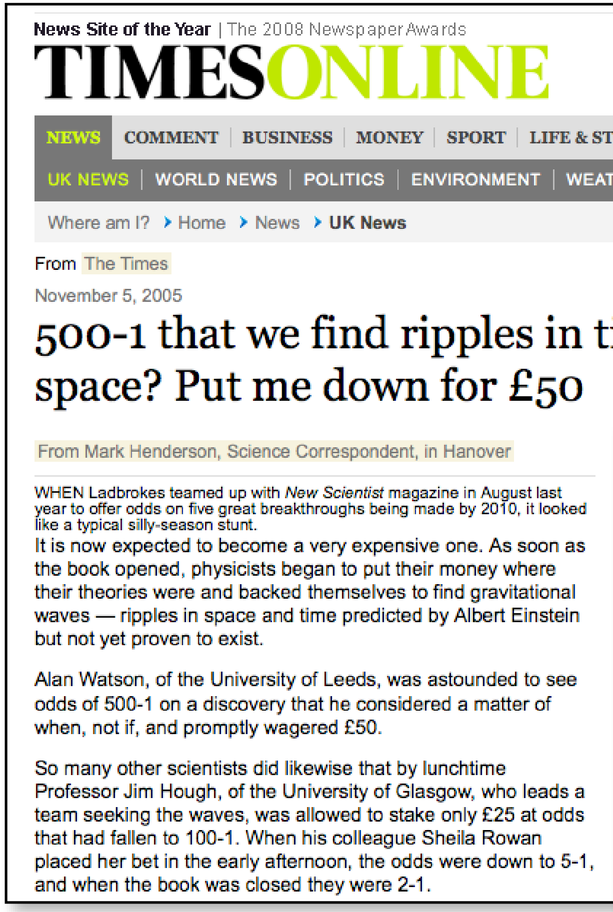


Overview

- What are gravitational waves?
- How can we convert gravitational waves into a digital data stream?
  - How does a GW interact with laser light?
  - How far can we boost up the signal by clever interferometry?
  - How to calibrate a gravitational wave detector?
  - What type of noise spoil our efforts?
- When will we detect the first gravitational wave?
- What will future gravitational wave detectors look like?

Betting on the detection of GW before 2010

- In 2005 Ladbrokes offered a bet: GW will be detected by 2010.
- It started with 500:1
- A few days later the odds were down to 2:1
- Finally they closed the bet.



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From The Times

November 5, 2005

500-1 that we find ripples in time and space? Put me down for £50

From Mark Henderson, Science Correspondent, in Hanover

WHEN Ladbrokes teamed up with *New Scientist* magazine in August last year to offer odds on five great breakthroughs being made by 2010, it looked like a typical silly-season stunt.

It is now expected to become a very expensive one. As soon as the book opened, physicists began to put their money where their theories were and backed themselves to find gravitational waves — ripples in space and time predicted by Albert Einstein but not yet proven to exist.

Alan Watson, of the University of Leeds, was astounded to see odds of 500-1 on a discovery that he considered a matter of when, not if, and promptly wagered £50.

So many other scientists did likewise that by lunchtime Professor Jim Hough, of the University of Glasgow, who leads a team seeking the waves, was allowed to stake only £25 at odds that had fallen to 100-1. When his colleague Sheila Rowan placed her bet in the early afternoon, the odds were down to 5-1, and when the book was closed they were 2-1.

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Some other interesting bets from Ladbrokes:

Odds on breakthroughs by 2010, offered by Ladbrokes in conjunction with *New Scientist*

GRAVITATIONAL WAVES
Will ripples in space-time, predicted by Einstein but never directly observed, finally be found? Starting price: 500-1; closing price: 2-1 Worth a punt? Definitely. Most experts expect the Ligo experiments that began yesterday to prove their existence

INTELLIGENT LIFE ON TITAN
Is Saturn's largest moon, recently studied by the Huygens probe, home to intelligent life? Starting price: 10,000-1; closing price: 10,000-1 Worth a punt? Not on your life. Scientists are confident there is no intelligent life in the Solar System (except on Earth)

HIGGS BOSON
Will the elusive "God particle", which theory suggests gives matter its mass but which has never observed, be detected? Starting price: 6-1; closing price: 2-1 Worth a punt? Yes. The Large Hadron Collider at the Cern laboratory will start experiments in 2007 and should find the Higgs — if it exists

FUSION POWER
Will a fusion power station be built that generates more energy than it consumes? Starting price: 100-1; closing price: 20-1 Worth a punt? No. Fusion has been "30 years away" for, well, at least 30 years. ITER, a £6bn experimental fusion reactor, will not even start operating until 2016

ORIGIN OF COSMIC RAYS
Can scientists prove where these high-energy particles that constantly bombard Earth come from? Starting price: 4-1; closing price: 3-1 Worth a punt? Perhaps. The Pierre Auger experiment in Argentina has been on the case since 2004, and stands a decent chance of success

www.telegraph.co.uk

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A world-wide network of large-scale gravitational-wave detectors

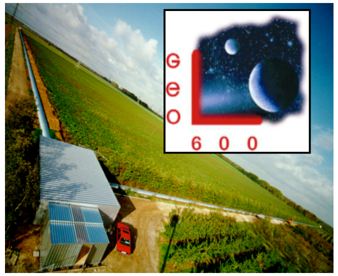
1st Generation

LIGO Hanford
1x 4km + 1x 2km

LIGO Livingston
4km

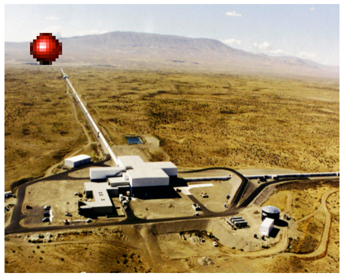
TAMA300
300 m

Virgo
3 km

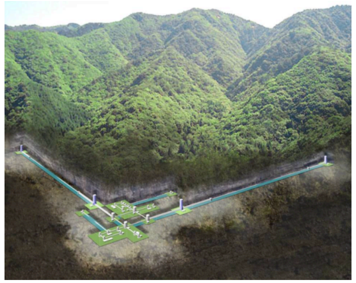


GEO 600
600 m

2nd Generation



Advanced LIGO



LCGT

Adv Virgo

GEO HF

A world-wide network of large-scale gravitational-wave detectors

1st Generation

So far the 1st Generation detectors did see any GW signal…

LIGO Ha
1x 4km + 1x 2km

LIGO Livingston
4km

TAMA300
300 m

Virgo
3 km

GEO 600
600 m

2nd Generation

The 2nd generation detectors will detect events on a monthly base!

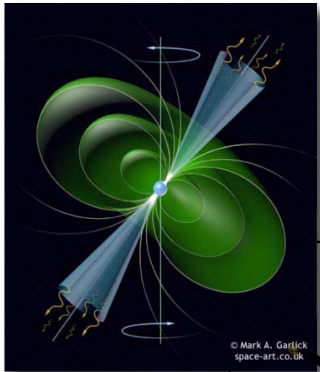
Advanced LIGO

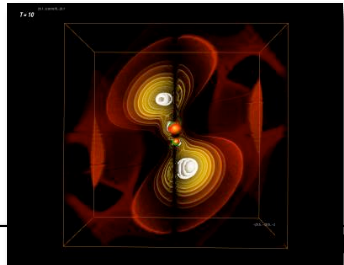
LCGT

Adv Virgo

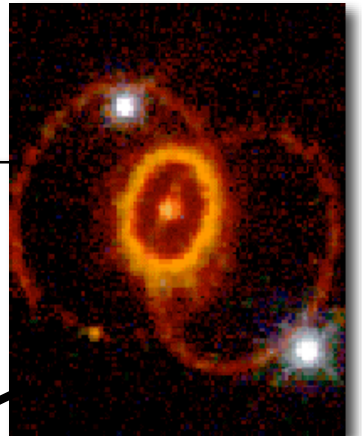
GEO HF

For which source shall we optimise the advanced detectors ?

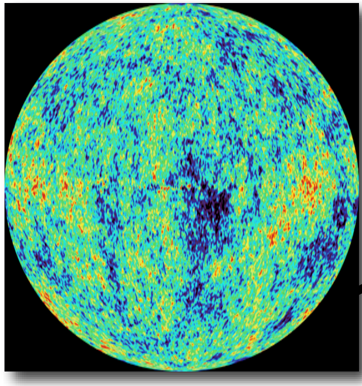


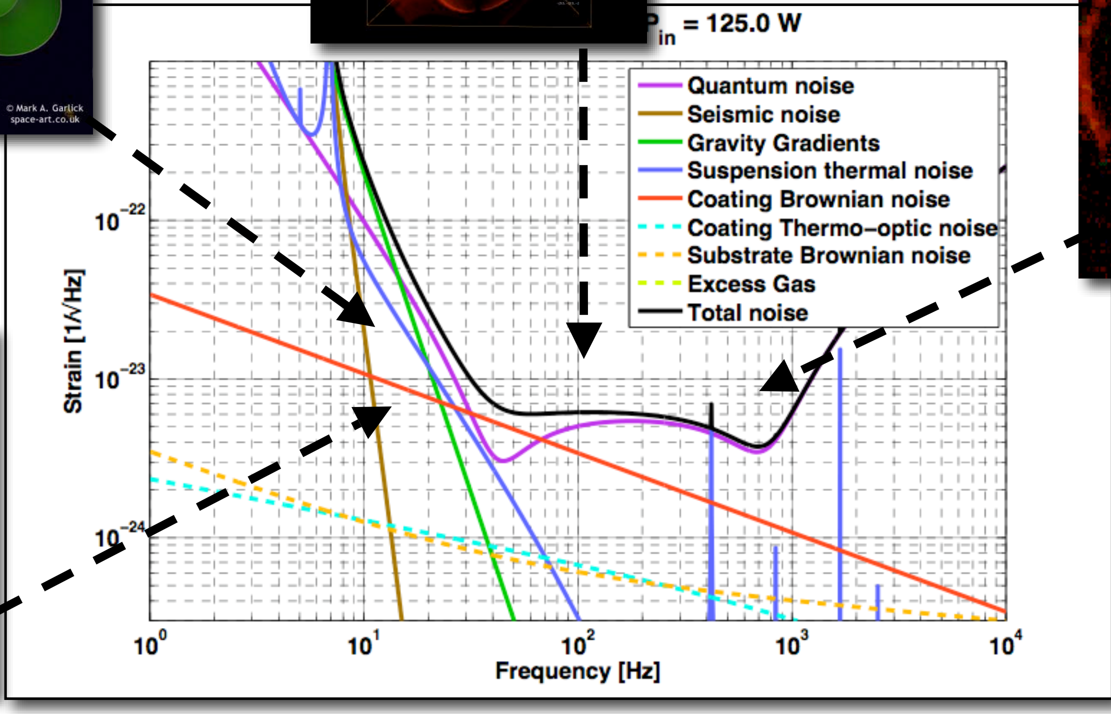


Inspirals:
Mid frequency



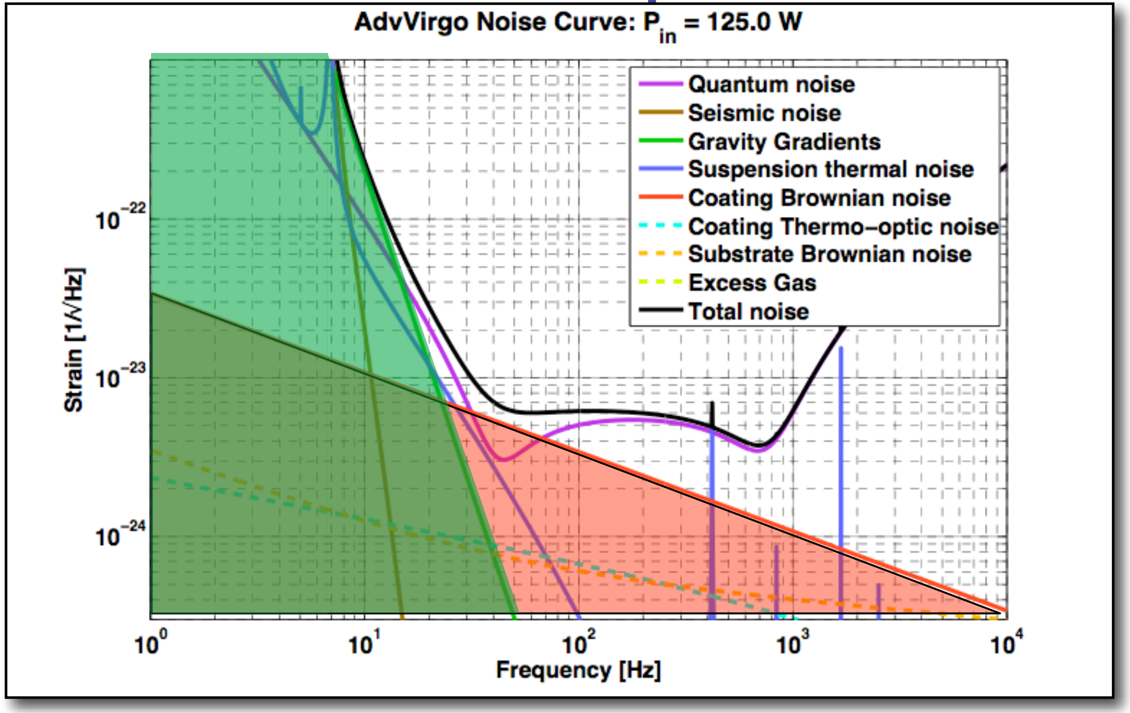
Pulsars +
Stochastic:
Low frequency





Supernovae:
High frequency

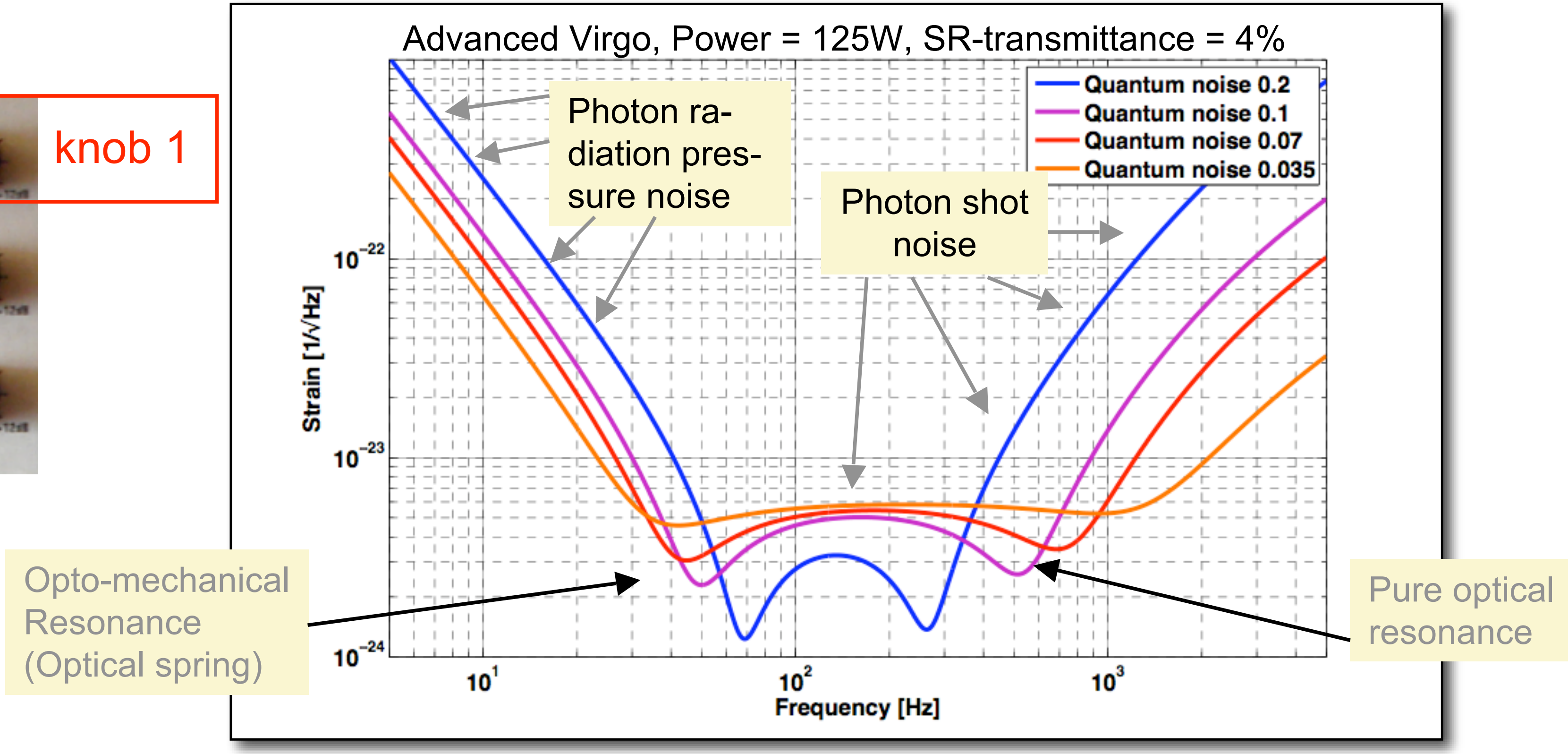
Limits of the optimization



- Our optimisation is limited by Coating thermal noise and Gravity Gradient noise.
- **<u>Quantum noise to be optimised!</u>**
- We have three knobs available for this optimisation: 1) Optical power, 2) Signal recycling tuning, 3) Signal Recycling trans-mittance

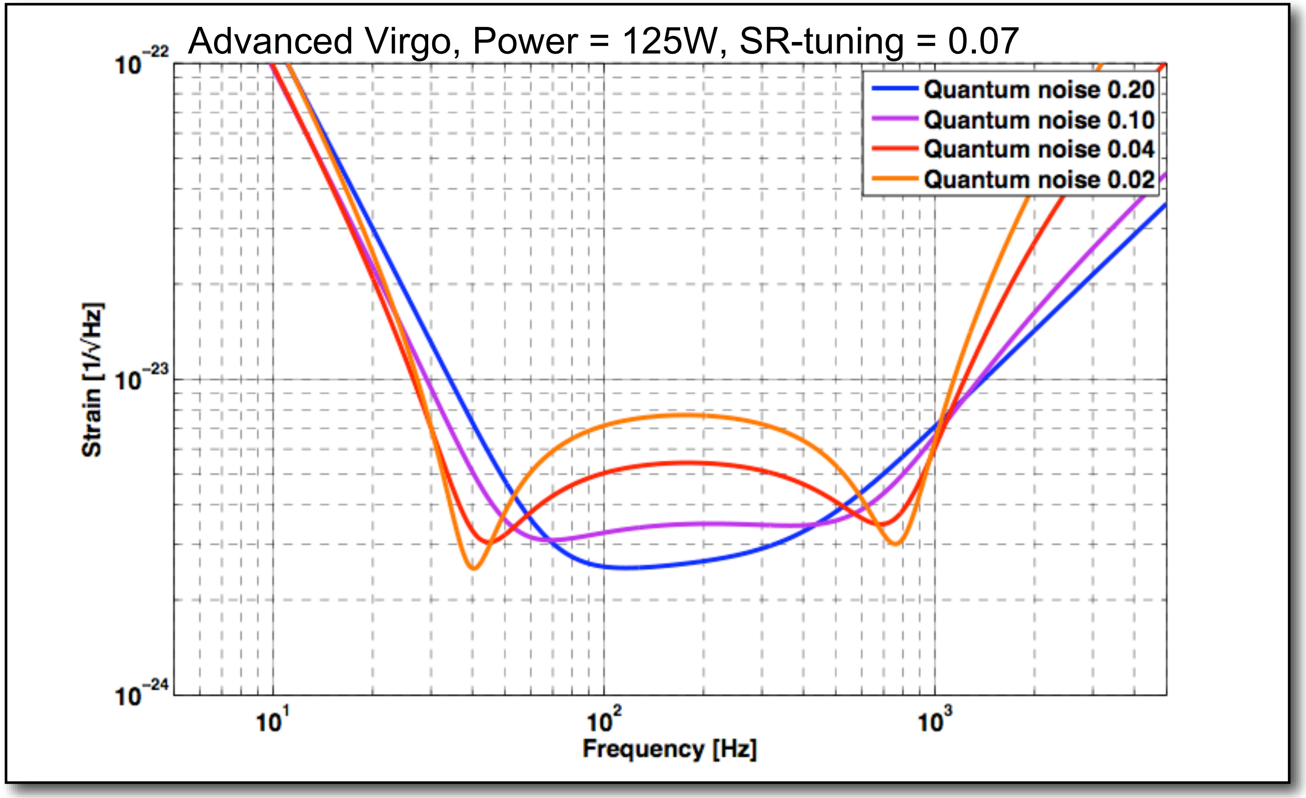
Optimization Parameter 1: Signal-Recycling (de)tuning

knob 1



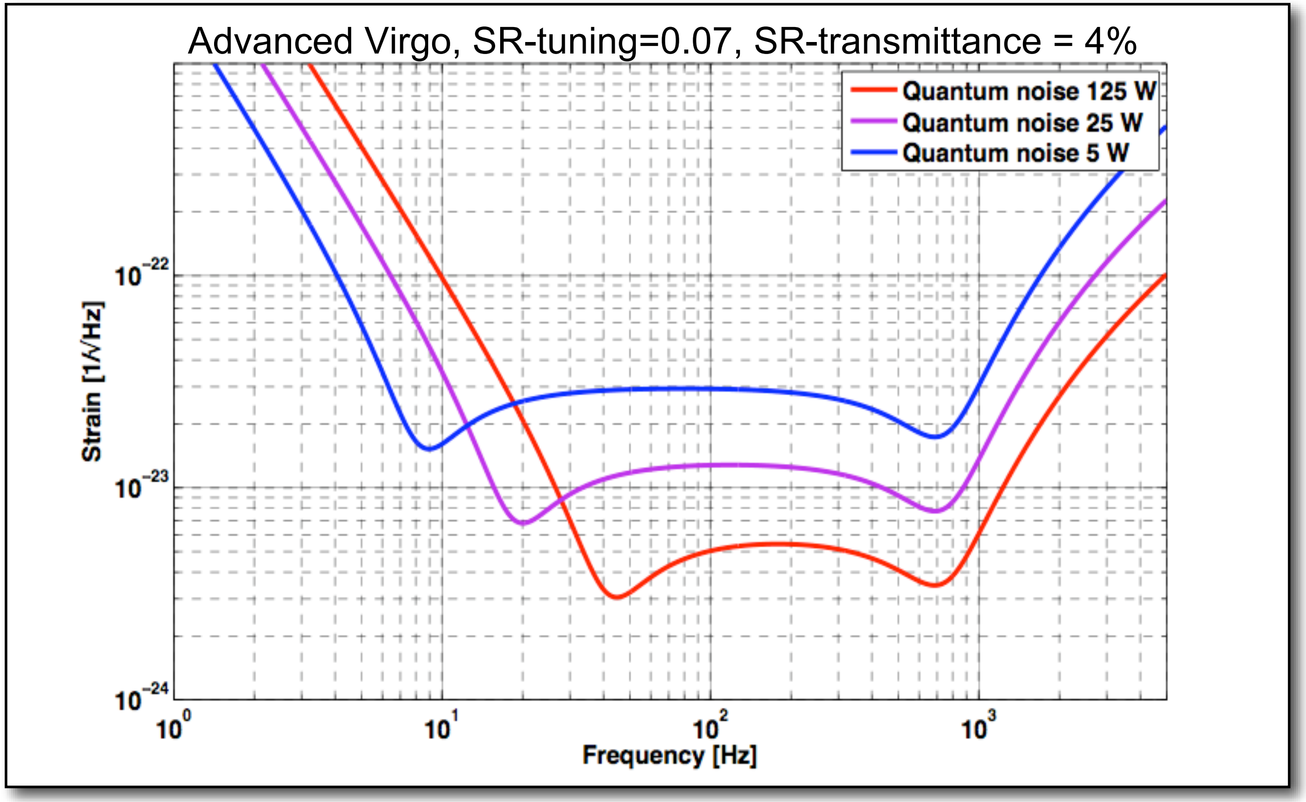
- Frequency of pure optical resonance goes down with SR-tuning.
- Frequency of opto-mechanical resonance goes up with SR-tuning

Optimization Parameter 2: Signal-Recycling mirror transmittance



- Resonances are less developed for larger SR transmittance.

Optimization Parameter 3: Laser-Input-Power



- High frequency sensitivity improves with higher power (Shotnoise)
- Low frequency sensitivity decreases with higher power (Radiation pressure noise)

Figure of merit: Inspiral

- Inspiral ranges for BHBH and NSNS coalesence:

Symmetric mass ratio

Frequency of last stable orbit (BNS = 1570 Hz, BBH = 220 Hz)

Total mass

Spectral weighting = $f^{-7/3}$

$$d = \frac{m^{5/6}}{\rho_0 \pi^{2/3}} \left(\frac{5\eta}{6}\right)^{1/2} \left[\int_0^{f_{\rm lso}} df \, \frac{f^{-7/3}}{S_h(f)}\right]^{1/2}.$$

Detector sensitivity

[1] Damour, Iyer and Sathyaprakash, Phys. Rev. D 62, 084036 (2000).
[2] B. S. Sathyaprakash, "Two PN Chirps for injection into GEO", GEO Internal Document

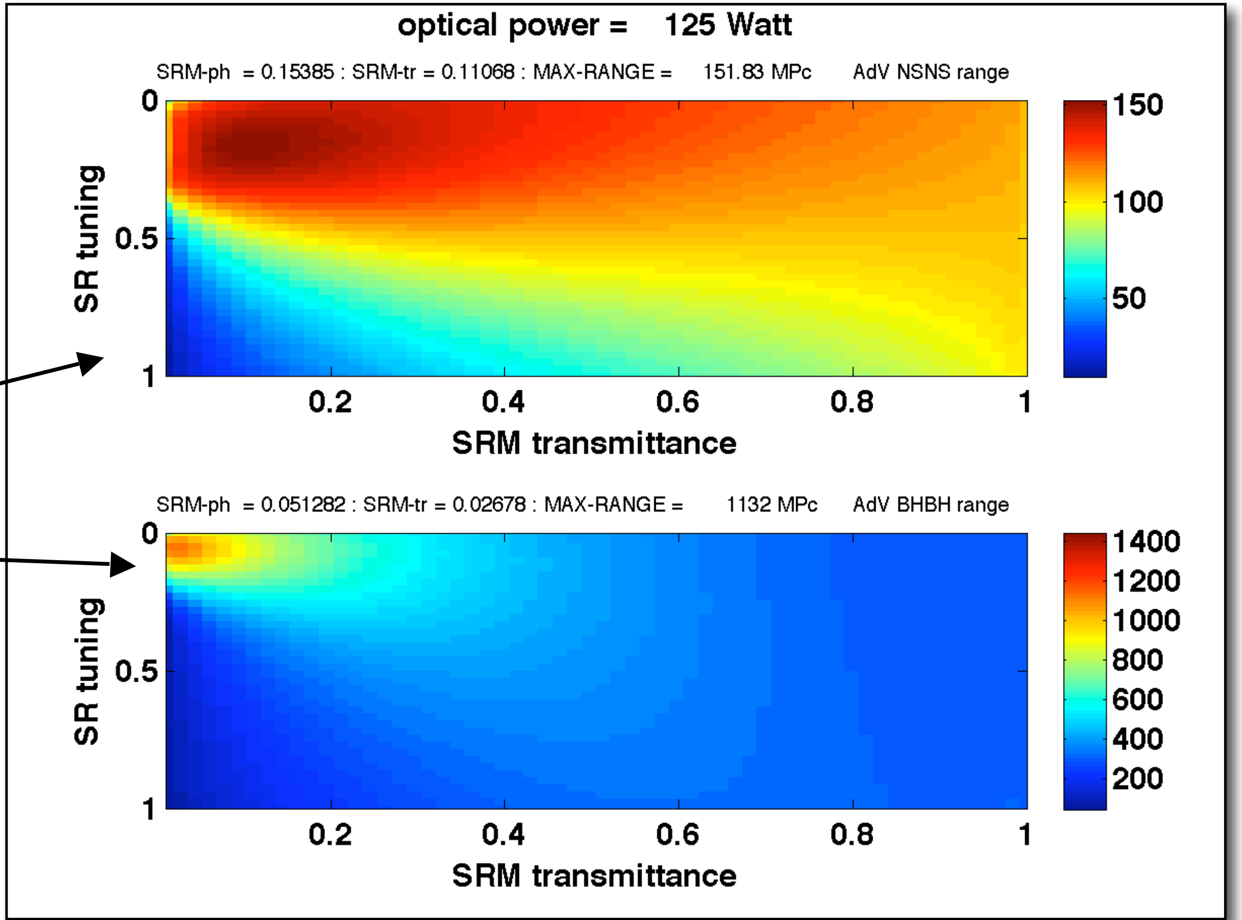
- Parameters usually used:
  - NS mass = 1.4 solar masses
  - BH mass = 10 solar masses
  - SNR = 8
  - Averaged sky location

Example: Optimizing 2 Parameters

- Inspiral ranges for free SR-tuning and free SRM-transmittance, but fixed Input power

NSNS-range

BHBH-range



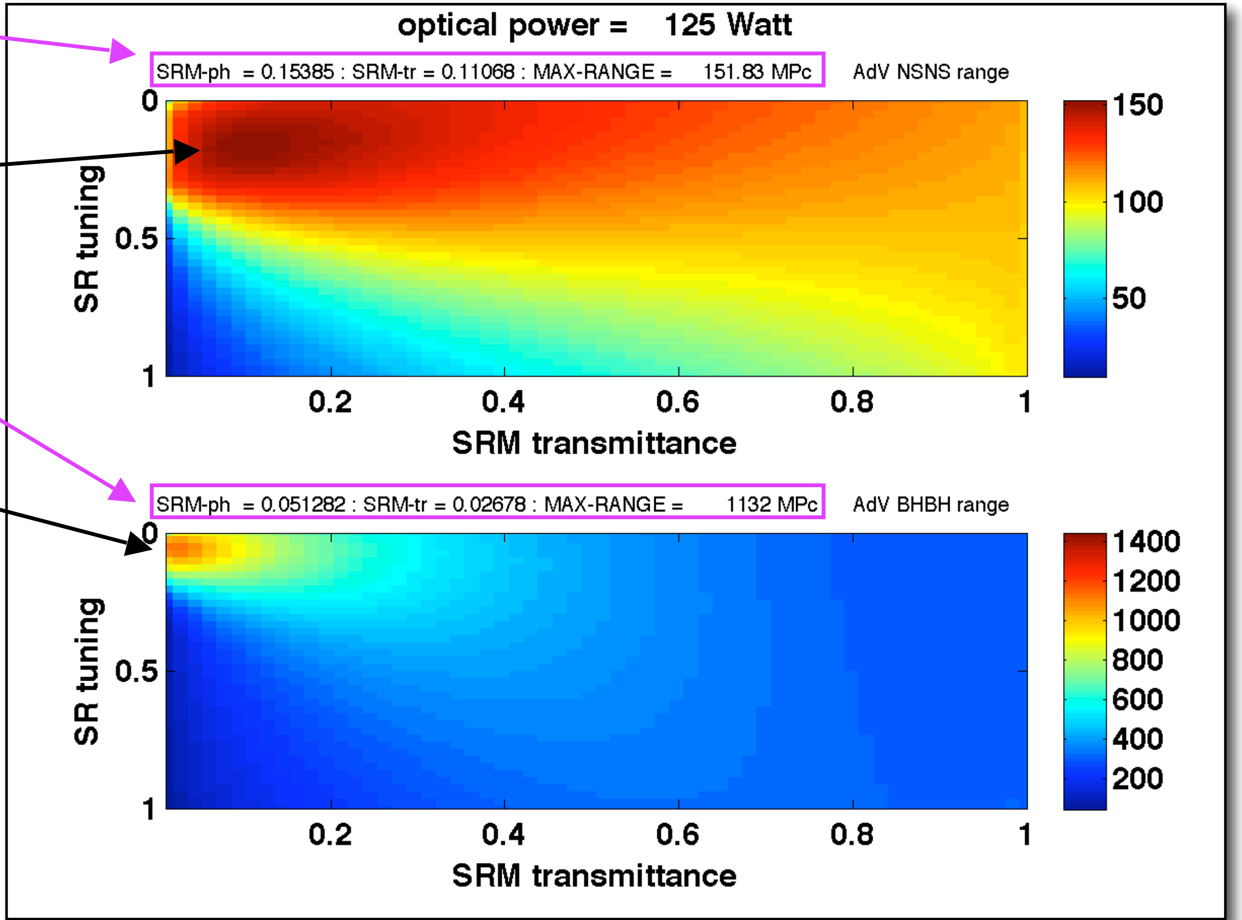
Example: Optimizing 2 Parameters

Parameters for maximum

Maximum NSNS-range

Parameters for maximum

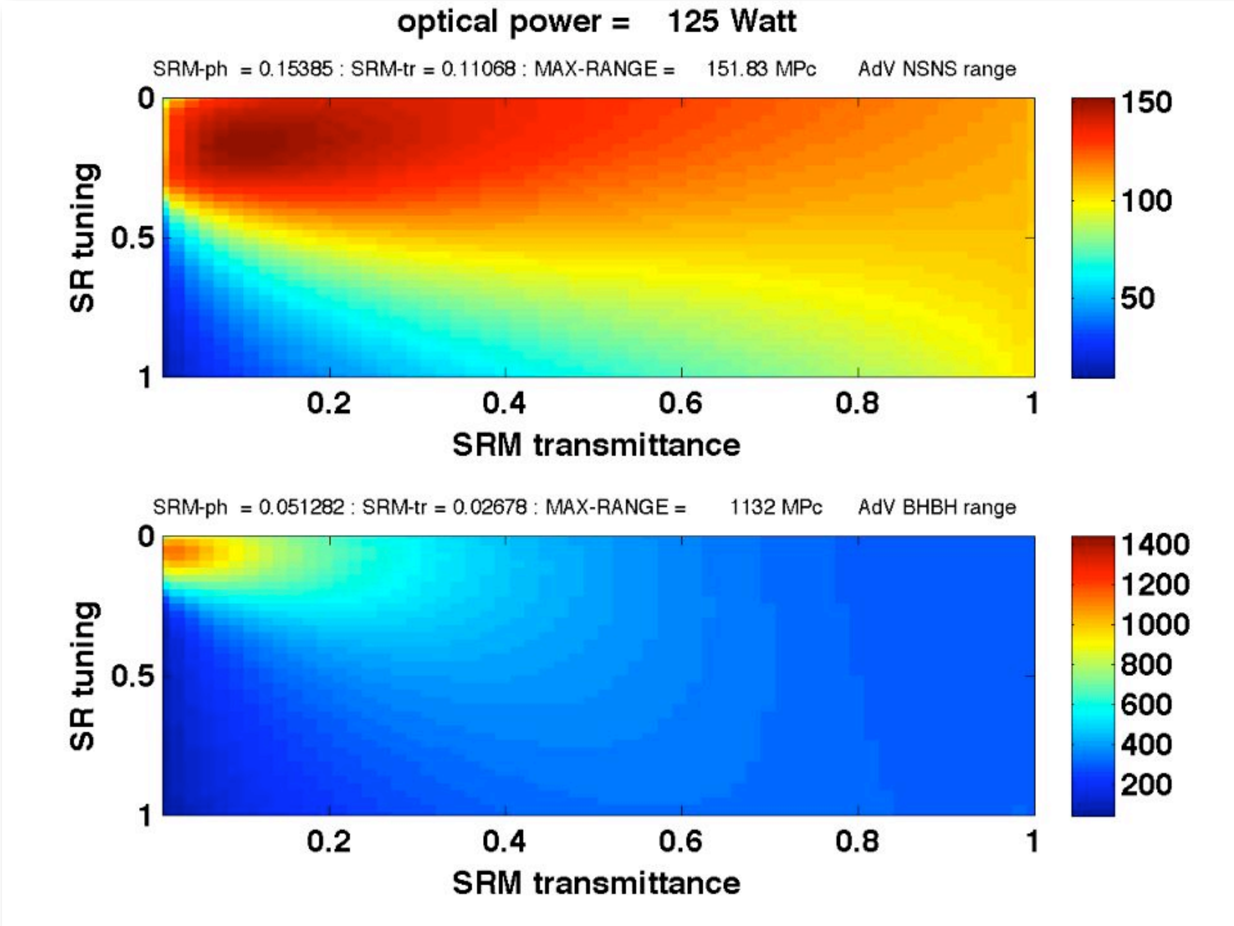
Maximum BHBH-range



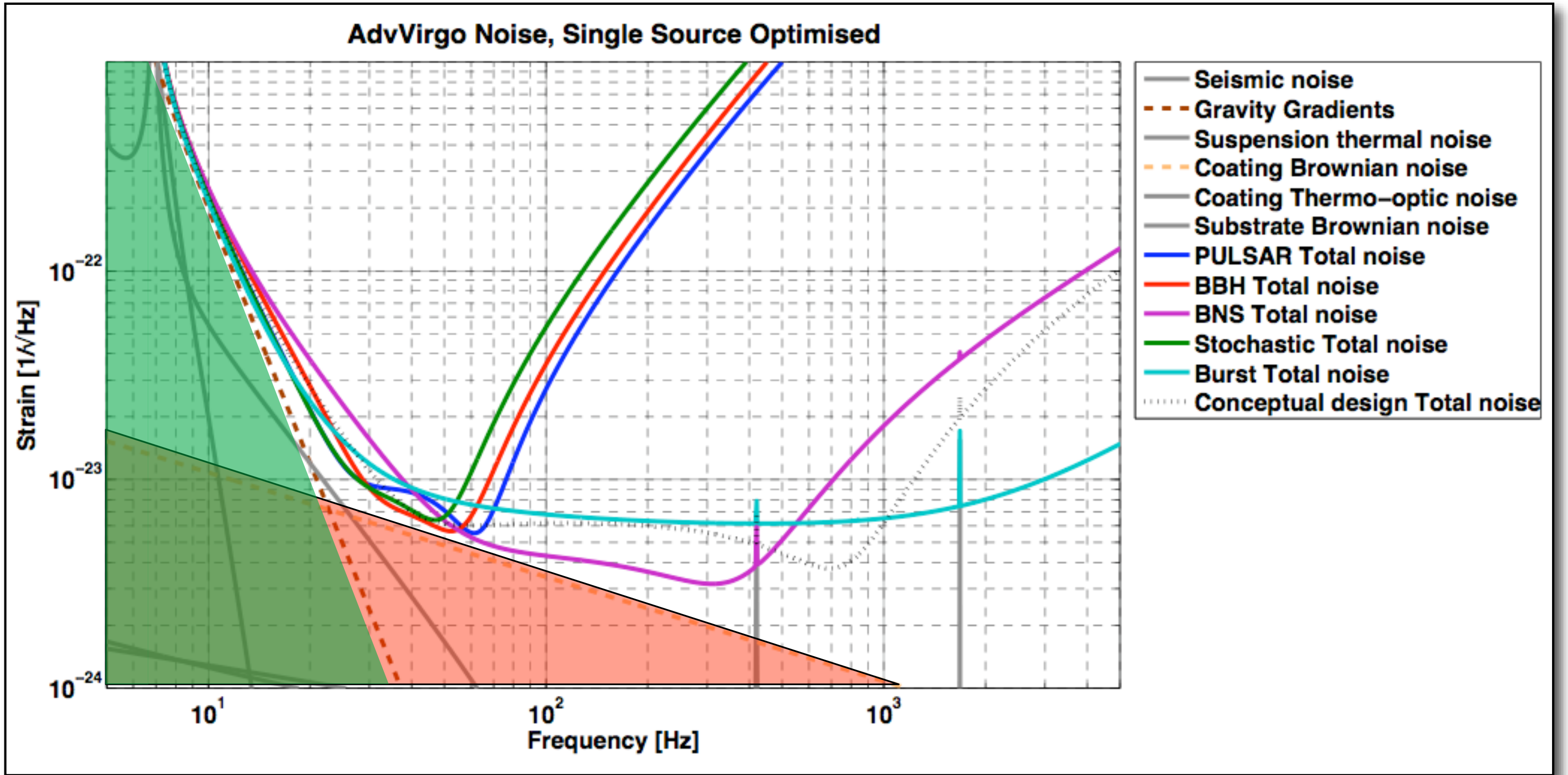
- Different source usually have their maxima at different operation points.
- It is impossible to get the maximum for BNS **AND** BBH both at the same time !

Example: Optimizing 3 Parameter for Inspiral range

- Scanning 3 parameter at the same time:
  - SR-tuning
  - SR-trans
  - Input Power
- Using a video to display 4th dimension.



Optimal configurations



Curves show the optimal sensitivity for a single source type.

Which is the most promising source?

Binary neutron star inspirals:

Based on observations of existing binary stars

Based on models of binary star formation and evolution

model	merger rate ($\mathrm{Myr}^{-1}\mathrm{MWEG}^{-1}$)	detection rate (yr^{-1})
empirical	3 - 190	0.4 - 26
A	12 - 19	1.6 - 2.6
B	7.6 - 12	1 - 1.6
C	68 - 101	9.2 - 14

Expected event rates seen by Advanced Virgo: ~1 to 10 events per year.

Binary neutron star inspirals are chosen to be the primary target for Advanced Virgo.

Binary black hole inspirals:

Model	$\mathcal{M}/M\_\odot$ range	$d_{eff-sight}$Mpc	merger rates Myr^{-1}	AdV detection rate yr^{-1}
A	$5-8$	613	$0.02-0.03$	$0.2-0.3$
C	$2.5-8.5$	545	$7.7-11$	$52-75$

C.Kim, V.Kalogera and D.Lorimer: “Effect of PSRJ0737-3039 on the DNS Merger Rate and Implications for GW Detection”, astro-ph:0608280 http://it.arxiv.org/ abs/astro-ph/0608280.

K.Belczynski, R.E.Taam, V.Kalogera, F.A.Rasio, T.Buli:, “On the rarity of double black hole binaries: consequences for gravitational-wave detection”, The Astrophysical Journal 662:1 (2007) 504-511.

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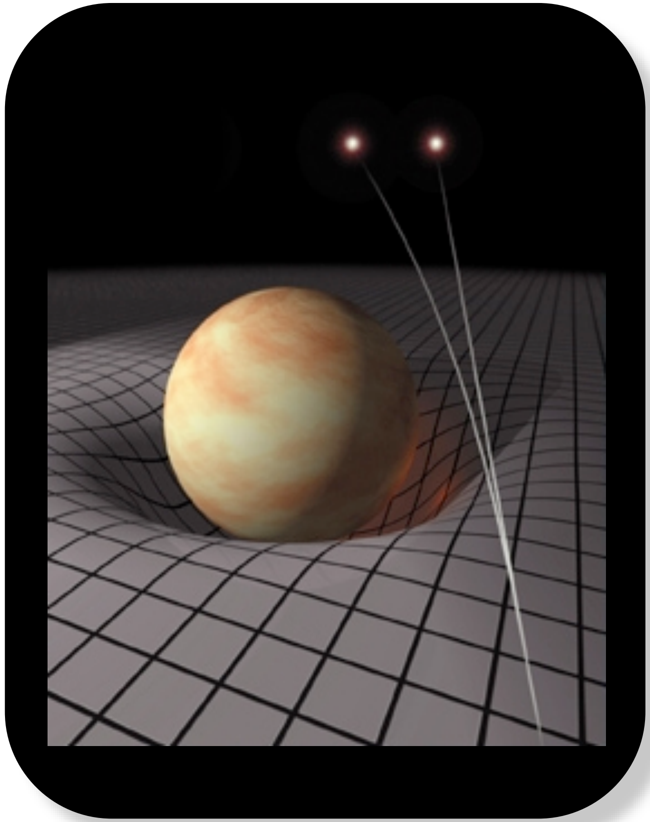
When will we detect gravitational waves ??

- When Advanced LIGO and Advanced Virgo come online **WE WILL SEE GRAVITATIONAL WAVES!**
- … if not, then something is completely **wrong** with our understanding of **General Relativity**.



Overview

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- How can we convert gravitational waves into a digital data stream?
  - How does a GW interact with laser light?
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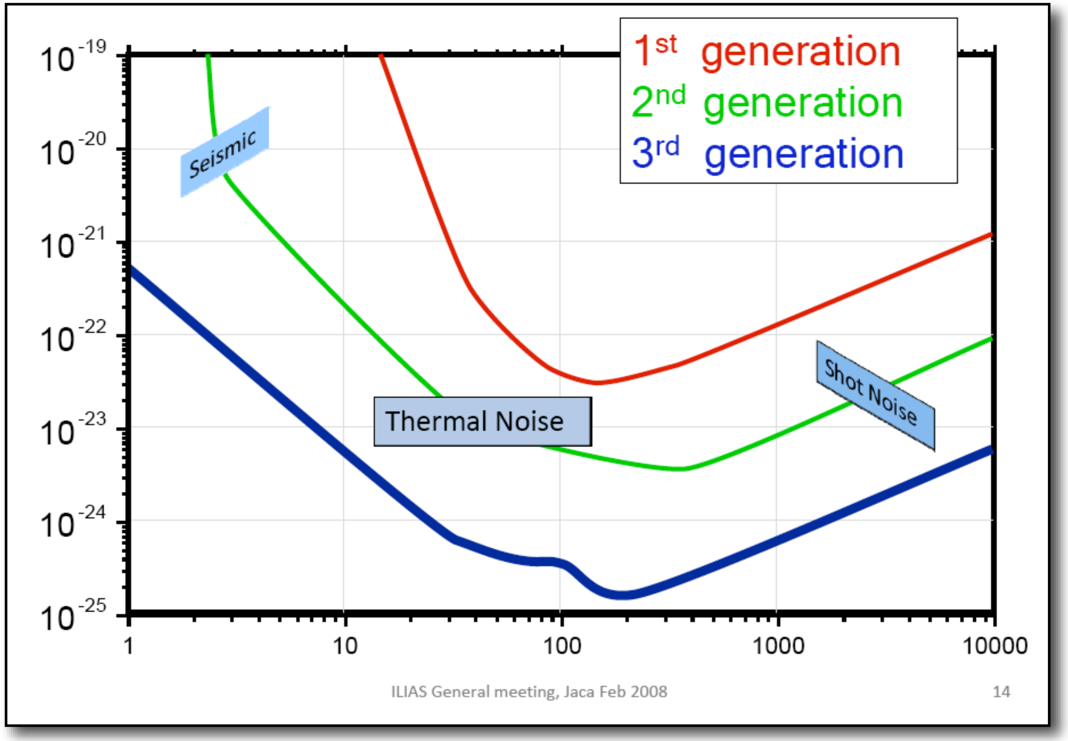
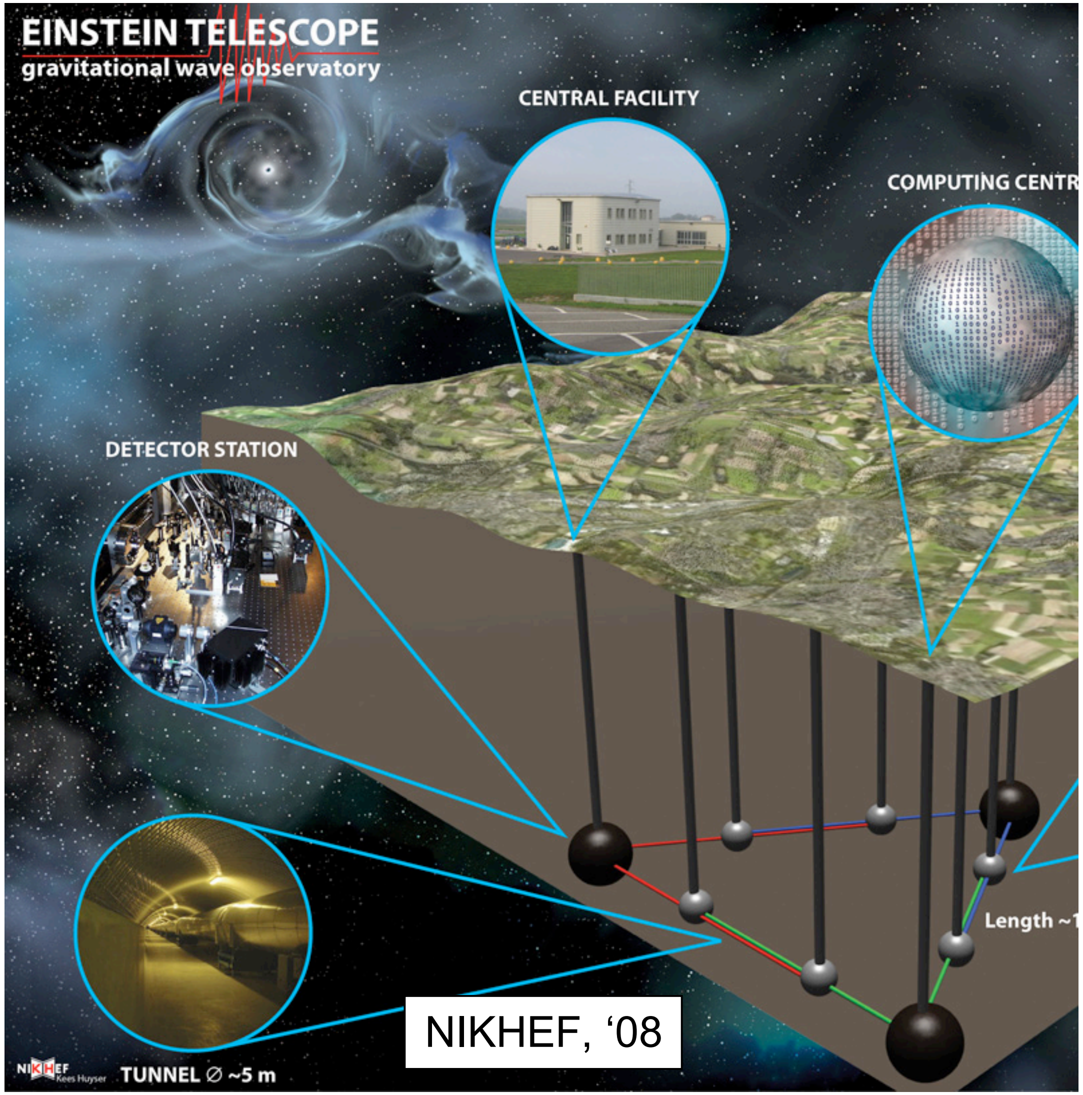
  - What type of noise spoil our efforts?
- When will we detect the first gravitational wave?
- $\boxed{\text{What will future gravitational wave detectors look like?}}$

Einstein GW Telescope

- 1st Proposal for a third generation detector.
- GEO and Virgo collaborations started design study within the FP7 framework.
- Aiming for:
  - 10 times better sensitivity than 2nd generation
  - Pushing observation band down to 1Hz
- http://www.et-gw.eu/



- Start around 2020(?)
- Underground location
- ~30km integrated tunnel length (?)
- New potential topologies:
  - Triangle made out of 3 Michelson interferometer (?)
- Plenty of new Science…



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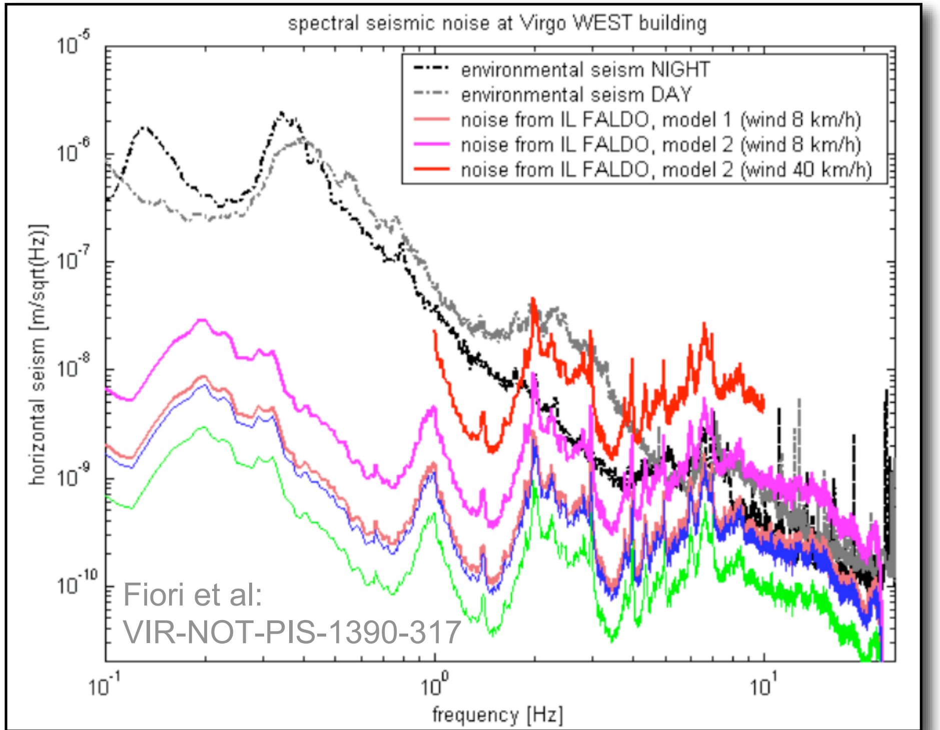
EGO

Tackling Gravity Gradient noise: going underground



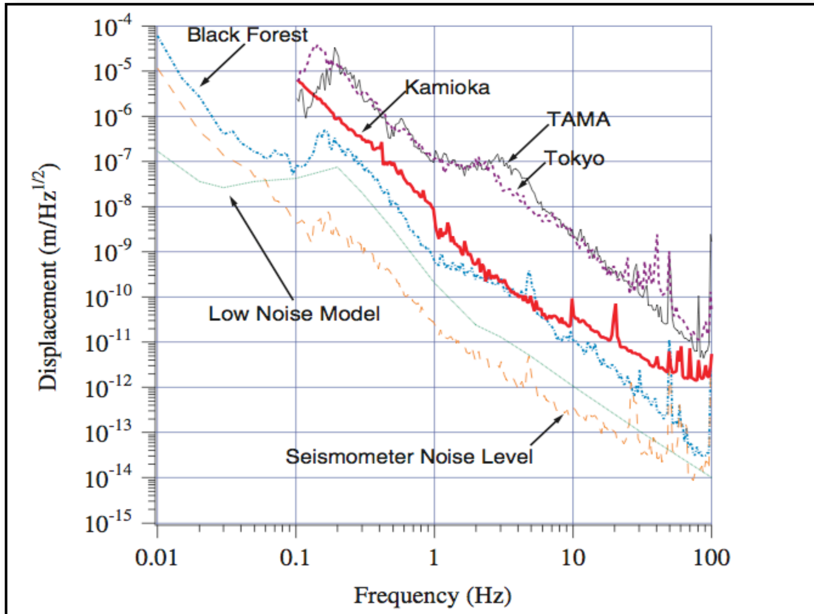


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

Ohasi et al: Class. Quantum Grav. **20** (2003) S599-607

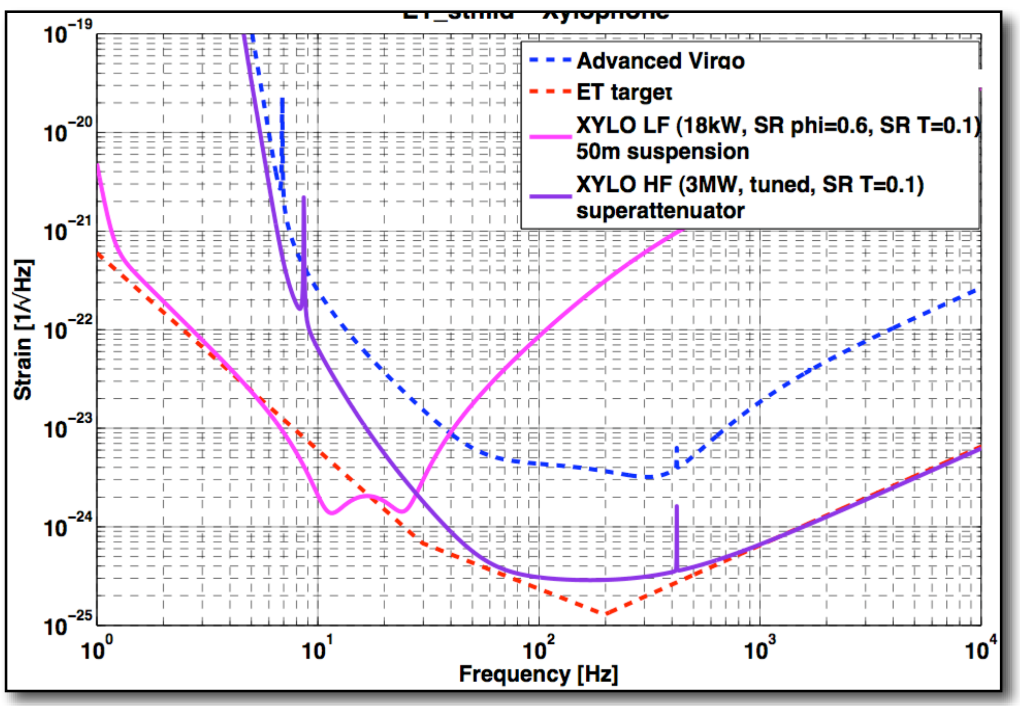
Surface (Pisa)

about $1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Underground (Kamioka)

about $5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Xyolophon: More than one detector to cover the full bandwidth



Low Frequency IFO: low optical power, cryogenic test masses, sophisticated low frequency suspension, underground, heavy test masses.

High Frquency IFO: high optical power, room temperature, surface location, squeezed light


If we do a good job on making our Gravitational wave detectors more sensitive …
… we have a chance to hear the symphony of the Universe soon !!
http://hubblesite.org/

Acknowledgements

Thanks to the LIGO Scientific collaboration, the GEO collaboration, Virgo Collaboration and their funding agencies.

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gra Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

VIRGO

INFN Padova-Tren
APC: Astroparticule et Cosmologie, Paris
ESPCI: Ecole Superieure de Physique et de Chimie Industrielles
EGO: European Gravitational Observatory
POLGRAW :Institute of Mathematics - Polish Academy of Sciences
INFN - Firenze/U
INFN - Genova
INFN - Napoli
INFN - Perugia
INFN - Roma 1
INFN - Pisa
INFN - Roma 2
Laboratoire d'Annecy-le-vieux de Physique des Particules
Laboratoire de l'Accelerateur Lineaire
Laboratoire des Materiaux Avances
NIKHEF: National Institute for Nuclear Physics and High Energy Physics
ARTEMIS: Observatoire de la Cote d'Azur - CNRS
RMKI:Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences

END